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RESEARCH MEMORANDUM

SKIN-TEMPERATURE TELEMETER FOR DETERMINING BOUNDARY-LAYER HEAT-TRANSFER COEFFICIENTS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The problem of aerodynamic heating of supersonic aircraft requires a knowledge of boundary-layer heat-transfer coefficients. One method of determining these coefficients involves the measurement of the transient skin temperature of a rocket-propelled test vehicle.

A method of telemetering this skin temperature using a small resistance wire pickup with a time constant of less than 0.003 second is described. Transmission is accomplished by the standard NACA radio telemeter. An experimental method of determining the response of the pickup to rapidly changing temperature is given.

An evaluation of the accuracy of this method of measuring the heat-transfer coefficient is given for a particular application. The errors contributed by the temperature pickup itself are negligible; the error caused by the telemeter is the greatest factor.

INTRODUCTION

The aerodynamic heating of skin surfaces is an important consideration in the development of supersonic aircraft. At high speeds, the stagnation of the boundary layer produces heat which is transferred to the exposed skin surfaces. This heat transfer is proportional to the difference between the boundary-layer temperature (that is, the temperature which the air would attain on an insulated surface under the same flow condition) and the skin temperature. The factor of proportionality is the heat-transfer coefficient.

At the Langley Laboratory of the NACA, this coefficient is being investigated by means of rocket-propelled test vehicles. From the flight of these missiles, the heat flow is calculated using the rate of change of skin temperature, while the temperature difference is obtained from

[redacted]

the measured skin temperature and the calculated boundary-layer temperature. Thus, the determination of the heat-transfer coefficient requires the telemetering of skin temperature against time and simultaneous measurements of velocity and free-air temperature. This paper is primarily concerned with the design of a sensing element for measuring skin temperature and the application of this instrument to the determination of boundary-layer heat-transfer coefficient.

SYMBOLS

c	specific heat of skin, British thermal units per pound per degree Fahrenheit
E	emissivity, dimensionless
h	convective heat-transfer coefficient, British thermal units per square foot per second per degree Fahrenheit
k	diffusivity of skin, square feet per second
l	thickness of skin, feet
Q	rate of heat flow per unit area from boundary layer to skin, British thermal units per square foot per second
RF	boundary-layer temperature recovery factor
t	time, seconds
T	temperature, degrees Fahrenheit
T_b	temperature of boundary layer, degrees Fahrenheit, defined as the temperature which the air would attain on an insulated surface under the same flow conditions
T_l	air temperature just outside the boundary layer, degrees Fahrenheit
T_p	temperature of pickup, degrees Fahrenheit
T_s	average temperature through the skin thickness, degrees Fahrenheit
T_o	stagnation temperature, degrees Fahrenheit
ΔT	temperature drop through skin, degrees Fahrenheit

w specific weight of skin, pounds per cubic foot

x distance, feet, from the inside surface of the skin

y distance, feet, from a cold bulkhead

λ effective time constant of skin, seconds

τ time constant of pickup, seconds; time required for a pickup to reach 63 percent of an applied step change in temperature

DISCUSSION OF PROBLEM

Theory.- The heat-transfer coefficient is given by

$$h = \frac{Q}{T_b - T_s} \tag{1}$$

provided there is no appreciable temperature gradient through the thickness of the skin. If all other heat flow to or from a particular area of the skin is negligible in comparison to the heat flow from the boundary layer, Q may be determined from

$$Q = lwc \frac{dT_s}{dt} \tag{2}$$

so that

$$h = \frac{lwc \frac{dT_s}{dt}}{T_b - T_s} \tag{3}$$

Thus, to determine h experimentally it is necessary that: (1) all heat transferred to or from the test area of the skin be accounted for; (2) the boundary-layer temperature be known; and (3) the temperature-sensing element accurately measure the instantaneous skin temperature. These three factors are discussed, and the magnitudes of errors in a specific application are given in the section entitled "Evaluation of Errors in a Specific Application."

Heat losses.- Heat losses or gains may consist of heat exchanged by radiation, heat flow to bulkheads and reinforcements, flow to air inside the missile, and to the temperature-sensing element.

Best accuracy will be obtained when the heat flow from the boundary layer is large compared to these heat losses, which occurs when a large temperature difference exists between the boundary layer and the skin; this condition may be easily obtained from the high accelerations possible in rocket-propelled vehicles.

Boundary-layer temperature.- The boundary-layer temperature can be determined from the definition of recovery factor

$$RF = \frac{T_b - T_l}{T_o - T_l} \tag{4}$$

Stagnation temperature T_o may be calculated from radiosonde data and velocity as measured by Doppler radar and/or internal accelerometer. The temperature of the air at any point just outside the boundary layer is determined from free-air temperature and the pressure distribution over the model. The boundary-layer temperature T_b is the same as the skin temperature where dT_s/dt is zero so that recovery factor RF may be calculated at this point. By assuming the recovery factor to be constant throughout the test, the boundary-layer temperature against time may be determined. A more complete discussion of the determination of boundary-layer temperature will be found in reference 1.

Temperature-sensing element.- In the tests made at the Langley Laboratory, skin temperatures ranged from 60° F to 500° F and changed at rates as high as 250° F per second. Since both the skin temperature and the rate of change must be determined, the sensing element must have a low heat capacity and an extremely short time lag in order to respond accurately to rapidly changing temperatures.

In addition, it must: (1) not disturb the boundary layer; (2) withstand high temperatures; (3) withstand high accelerations; (4) be usable with the standard NACA radio telemeter; and (5) be stable and easily calibrated.

Among the various types of temperature-sensing elements considered were thermal expansion measuring devices, thermocouples, and resistance wire pickups. The principal reason for considering an expansion measuring system was that its response to temperature changes would be instantaneous; however, any such scheme is inherently difficult since it requires a comparison of a dimension of the skin to a reference dimension which is unaffected by temperature changes or acceleration forces.

A thermocouple meets all the requirements previously listed except that difficulties in telemetering a small voltage make it impractical for this application.

Although the usual type resistance wire temperature pickup has a long time lag, an installation consisting of a fine platinum wire cemented directly to the inside surface of the skin was found to possess almost instantaneous response characteristics and to meet all other requirements.

RESISTANCE WIRE PICKUP

Dynamic response.- To determine the response of resistance wire pickups to rapid changes in temperature, preliminary investigations were made by cementing various sizes of wire to bronze strips ($1.5 \times 0.3 \times 0.003$ in.) using from one to three 0.0002-inch-thick layers of Dow Corning 993 varnish. The strip was connected across a direct-current voltage source as shown in figure 1.

When the switch was closed a heavy surge of current passed through the strip until the circuit was opened by the fuse. The bronze strip could be heated very suddenly in this manner, and the pickup wire response recorded by connecting the direct-current bridge to a recording cathode-ray oscilloscope. A plot of a record obtained for a 0.0005-inch pickup wire is shown in figure 2. The following points may be noted:

(a) Trace deflection is nearly proportional to the temperature of the wire.

(b) At zero time, the switch was closed; the surge of current in the strip induced a voltage in the pickup circuit causing the impulses during the first 0.002 second.

(c) At 0.004 second, the fuse opened, as shown by the impulse in the pickup circuit.

(d) After 0.035 second, the temperature of the pickup is not changing, indicating very little heat flow to the surroundings. The heat mass of the pickup is small so that there is little heat flow from the strip; therefore, the strip temperature after 0.004 second must be nearly constant since no heat was added or lost.

(e) Change in the temperature of the pickup after 0.004 second must be indicative of the response characteristic of the pickup.

Since the pickup is separated from the skin by only a very thin layer of varnish, the rate of change of temperature of the pickup is approximately proportional to the instantaneous temperature difference between the pickup and the skin where the constant of proportionality is $1/\tau$.

Thus, the time constant τ may be determined from

$$T_s - T_p = \tau \frac{dT_p}{dt} \tag{5}$$

The quantities $(T_s - T_p)$ and dT_p/dt may be measured from the record (using arbitrary temperature units) so that τ may be calculated.

Figure 3 shows the results of several pickups tested in this manner. The pickup response does not exactly follow equation (5) but variations in the values of τ are not significant in this application.

Installation.- In the actual installation of the pickup, the problem of connecting lead wires was simplified by using Wollaston wire. A silver wire of 0.002-inch diameter with a platinum core of 0.0002-inch diameter was used since it could be readily attached to the skin with a layer of varnish only a few ten-thousandths inch thick. Before installation, the silver was removed from a portion of the wire by dissolving in nitric acid, leaving a bare platinum wire with low-resistance silver leads.

To cement the wire to the skin, Dow Corning 993 varnish (thinned 2:1) was brushed on the inside surface and baked for 2 hours at 500° F after which the lead wire and the pickup were brushed down with more varnish and baked as before. The total thickness of the final installation was then about 0.0005 inch.

The silver leads were soldered to terminals located several inches away from the exposed platinum wire.

TELEMETER

Telemeter system.- In the NACA telemeter system, a pickup instrument controls the frequency of a subcarrier oscillator. Several such oscillators, operating on different frequencies between 100 and 200 kilocycles, simultaneously modulate a 118-megacycle carrier frequency, which is transmitted from the missile to the ground receiving station. The ground station separates the individual subcarrier frequencies. These frequencies are then fed into individual discriminators which produce a direct-current voltage proportional to the frequency deviation of the subcarrier oscillator. The direct-current voltages are recorded on multichannel oscillographs.

Subcarrier oscillator.- A resistance may be made to control the subcarrier oscillator frequency by shunting across a portion of the resonant L-C circuit as indicated in figure 4. The oscillator may be adjusted to operate at any subcarrier frequency, and, when properly adjusted, frequency will vary linearly over a 2-kilocycle bandwidth corresponding to a resistance change of approximately 100 to 180 ohms.

The high-frequency current through the pickup is so small that it does not affect the pickup temperature.

Calibration.- Since the time lag of the pickup is known to be negligible, only a static calibration of the pickup is required; however, it is not practical to obtain a calibration of recorder film deflection against temperature directly, because the oscillator frequency would drift during the long periods required to reach stable temperatures and because the ground station must be calibrated at the time of the test. Therefore, three separate calibrations are necessary: (1) pickup resistance against temperature, (2) subcarrier oscillator frequency against resistance, and (3) recorder film deflection against frequency.

Accuracy.- The errors in the telemeter system due to instability of the electronic circuits, calibration, and reading errors cannot be known exactly, but from experience a conservative estimate of these errors is in the order of 2 percent of full scale. The only time lag introduced by the telemeter is that of the recorder used and is in the order of 0.003 second.

EVALUATION OF ACCURACY IN A SPECIFIC APPLICATION

Description of test vehicles and flights.- The rocket test vehicles used at Langley are RM-10 models, 12 inches in diameter by 146.5 inches long, powered by Deacon rocket motors. Skin-temperature pickups are located at various stations throughout the length of the model. The models are ground launched and reach a maximum Mach number of 2.5 within 3.2 seconds. More detailed description of these models is given in reference 1.

Each test station must be carefully chosen with respect to rates of change of temperature expected and to the proximity of reinforcements, bulkheads, and internal structure. As an illustrative example, the errors encountered at station 86 (located 86 in. from the apex of the nose) are discussed in the following paragraphs. The inside diameter of the missile at this station is 11.63 inches and the skin is made of 0.0933-inch magnesium. The 6-inch-diameter rocket motor is located in this section and the annular space between rocket motor and the skin is occupied by air only. The average specific heat c of the magnesium skin is 0.25 British thermal unit per pound °F and the specific weight w is 113.0 pounds per cubic foot. The telemetered skin temperature and the calculated boundary-layer temperature are shown in figure 5.

Heat flow to bulkheads.- Appendix A shows that a pickup should be installed at least 6 inches from a bulkhead. If this is done, the error in h due to lateral heat flow from the skin area to colder bulkheads will be small as indicated in figure 6.

Radiation.- Radiation errors include radiation from the sun to the skin, radiation from the skin to the surrounding atmosphere, and radiation from the inside surface of the skin to the internal rocket motor. The temperature of the rocket motor rises only a few degrees above the temperature of the surrounding atmosphere which is assumed to be 70° F. Radiation from the sun was found to be negligible since the rays are slanting and the exposure is intermittent (due to the varying roll and pitch angle of the missile).

The approximate radiation from the skin is therefore

$$2(17.3)E \times 10^{-10}\left[(460 + T_s)^4 - (460 + 70)^4\right]\frac{\text{Btu}}{\text{ft}^2\text{hr}} \qquad (6)$$

where E is approximately 0.1. The percent error in h is shown in figure 6.

Heat flow to the inside air.- Due to the lack of a more extensive knowledge of transient convection currents inside the missile under high accelerations, the rate of heat flow to the inside air has not been exactly determined; however, the heat-transfer coefficient to the inside air is much smaller than the boundary-layer heat-transfer coefficient, and the temperature differences existing on the outside are greater than on the inside, except in the vicinity where $T_s = T_b$. Moreover, the heat capacity of the inside air is very small compared to that of the skin. Hence, the heat flow to the inside must be negligible except when the heat flow from the boundary layer is near zero.

Time-lag errors in pickup.- Since the 0.0002-inch wire used in this installation is smaller than the wires shown in figure 3, the time constant will be less than 0.003 second. The error in T_s will then be $-0.003\,\frac{dT_s}{dt}$ and the error in $\frac{dT_s}{dt}$ will be $-0.003\,\frac{d^2T_s}{dt^2}$.

Temperature drop through the skin.- The inside surface temperature of the skin differs from the outside, causing an error in T_s and dT_s/dt. Appendix B shows that the temperature drop through the skin is very nearly equal to

$$\Delta T = \lambda \frac{dT_s}{dt} \tag{7}$$

where

$$\lambda = \frac{1}{2} \frac{l^2}{k} = 0.0318 \text{ second} \tag{8}$$

The form of equation (7) suggests that λ may be regarded as the "time constant" of the skin, and may be added to the pickup time constant and the recorder time constant to give the total error in T_s due to time lags.

$$-(0.003 + 0.003 + 0.0318) \frac{dT_s}{dt} = -0.038 \frac{dT_s}{dt} \tag{9}$$

The corresponding error in h is plotted in figure 6.

The error in dT_s/dt is shown in appendix B

$$-\frac{1}{2} \lambda \frac{d^2T_s}{dt^2}$$

This may also be added to the time-lag error of the pickups and recorder so that the total error in dT_s/dt is

$$-\left(0.003 + 0.003 + \frac{0.0318}{2}\right) \frac{d^2T_s}{dt^2} = -0.022 \frac{d^2T_s}{dt^2}$$

The corresponding error in h is plotted in figure 6.

Boundary-layer temperature errors.- An error will be encountered in the calculation of boundary-layer temperature, but this consideration is beyond the scope of this paper.

Errors in l, w, and c.- Some errors will be introduced in the determination of l, w, and c of the skin. If reasonable care is used, these errors will be small.

Telemeter errors.- To estimate the error in the heat-transfer coefficient resulting from the radio telemeter system inaccuracy, a fixed error of 1 percent of full scale plus a drift error which varied from 0 to 1 percent throughout the first 17 seconds of the flight was assumed. The error in h due to these combined errors is shown in figure 6.

TEST RESULTS

As a check on the instrumentation, two pickups were mounted at the same station; the telemetered temperatures from the pickups agreed within 4° F which was 1 percent of full-scale temperature range. A similar check at another station also showed 1-percent agreement.

The temperatures actually telemetered from station 86 of the test vehicle are given in figure 5.

The recovery factors and heat-transfer coefficients obtained by the instrumentation described are in good agreement with theoretical and experimental values previously obtained by other investigators as discussed in reference 1. It was also noted that the values of heat-transfer coefficient obtained when heat flowed from the boundary layer to the skin were in good agreement with the values obtained when heat flowed in the reverse direction.

CONCLUDING REMARKS

The pickup described herein has a low heat capacity and an extremely fast response and is readily adaptable to radio telemetering. It is ideally suited to the measurement of boundary-layer heat-transfer coefficients provided test stations are carefully selected and data are obtained when large temperature differences exist between the boundary layer and the test surface.

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APPENDIX A

HEAT FLOW TOWARD COLD BULKHEADS

If a bulkhead is in direct contact with the skin, heat will flow toward the bulkhead. This heat flow will cause an error in the determination of the heat-transfer coefficient.

Referring to figure 7, heat flow from the boundary layer would cause the skin temperature to rise according to the function T_s in figure 5 except in the vicinity of the bulkhead, where the skin temperature will be considerably lower due to the increased heat mass. Thus, the skin temperature at the pickup location, a distance y from the bulkhead, would also be lowered. In order to estimate this effect, assume that the heat flow from the boundary layer is such that the skin temperature is the step function $T_k(t - 3.5)$ shown in figure 5. Also, assume that the bulkhead has a large mass and remains cold. (This is a more severe condition than actually exists.) The temperature function y feet from the bulkhead is then (see reference 2, p. 118, problem 8)

$$T(y,t) = 230 \text{ erf } \frac{y}{2\sqrt{k(t - 3.5)}} + 53.5$$

Figure 8 shows a plot of this temperature function at various distances from the bulkhead.

The actual slope of T_s plotted against time curve, after 10 seconds, is approximately -8° F per second. The heat flow to the bulkheads will tend to make this in error by the slope of the curves found in figure 8. The percent error resulting is plotted in figure 9 for $y = 5$ and 6 inches.

Thus, in order to keep the error small, it is necessary to locate the pickup at least 6 inches from a bulkhead; however, the actual error will be less than that shown, since the bulkhead will also become heated.

APPENDIX B

TEMPERATURE DROP THROUGH THE SKIN

In order to show that the temperature through the skin is proportional to the rate of change of temperature, consider a thin slab (fig. 10) insulated on one side with a temperature $T(l,t)$ applied to the other side, where

$$T(l,t) = A + Bt^4 \qquad 0 < t < 3.5$$

and

$$A = 53.5$$

$$B = 0.867$$

This function is plotted in figure 5. $T(x,t)$ satisfies the following conditions:

$$T_t(x,t) = kT_{xx}(x,t) \qquad 0 < x < l, \quad t > 0$$

$$T(x,o) = A \qquad 0 < x < l$$

$$T_x(o,t) = 0$$

$$T(l,t) = A + Bt^4$$

Let

$$\Delta T(t) = T(l,t) - T(o,t)$$

The solution of the above equations for the first 3.5 seconds gives (see reference 2, p. 193, and p. 196 problem 6)

$$\Delta T(t) = \frac{16B}{\pi}\left\{t^3\left(\frac{A_1}{a_1} + \frac{A_2}{a_2} + \frac{A_3}{a_3} + \ldots\right) - 3t^2\left(\frac{A_1}{a_1^2} + \frac{A_2}{a_2^2} + \frac{A_3}{a_3^2} + \ldots\right) + \right.$$
$$6t\left(\frac{A_1}{a_1^3} + \frac{A_2}{a_2^3} + \frac{A_3}{a_3^3} + \ldots\right) - 6\left[\frac{A_1}{a_1^4}\left(1 - e^{-a_1 t}\right) + \right.$$
$$\left.\left.\frac{A_2}{a_2^4}\left(1 - e^{-a_2 t}\right) + \ldots\right]\right\}$$

where

$$A_1 = 1, \qquad a_2 = \frac{1^2\pi^2 k}{4l^2}$$

$$A_2 = -\frac{1}{3}, \qquad a_2 = \frac{3^2\pi^2 k}{4l^2} = 9a_1$$

$$A_3 = \frac{1}{5}, \qquad a_3 = \frac{5^2\pi^2 k}{4l^2} = 25a_1$$

$$\begin{matrix} \vdots & \qquad & \vdots \\ \text{etc.} & \qquad & \text{etc.} \end{matrix}$$

The significant term (when t is not too small) is

$$\begin{aligned} \Delta T(t) &= \frac{16B}{\pi} \frac{A_1}{a_1} t^3 \left(1 - \frac{1}{27}\right) \\ &= \frac{4}{\pi} \frac{0.963}{a_1} \frac{dT_s}{dt} \\ &= \frac{16l^2}{\pi^3 k}(0.963)\frac{dT_s}{dt} \\ &= 0.496\frac{l^2}{k} \frac{dT_s}{dt} \\ &= \lambda \frac{dT_s}{dt} \end{aligned}$$

where

$$\lambda \doteq \frac{1}{2} \frac{l^2}{k}$$

This is also true for functions of T_s of lower degree than 4; hence, this equation holds throughout the entire flight.

The average temperature through the skin is approximately

$$T_s = \frac{T(l,t) + T(o,t)}{2}$$

Then

$$\frac{dT_s}{dt} = \frac{T_t(l,t) + T_t(o,t)}{2}$$

and the error in measuring the slope of the average skin temperature is

$$T_t(o,t) - \frac{dT_s}{dt} = - \frac{T_t(l,t) - T_t(o,t)}{2}$$

$$= - \frac{\lambda}{2} \frac{d^2T_s}{dt^2}$$

REFERENCES

1. Chauvin, Leo T., and deMoraes, Carlos A.: Correlation of Supersonic Convective Heat-Transfer Coefficients from Measurements of the Skin Temperature of a Parabolic Body of Revolution (NACA RM-10). NACA RM L51A18, 1951.

2. Churchill, Ruel V.: Modern Operational Mathematics in Engineering. McGraw-Hill Book Co., 1944.

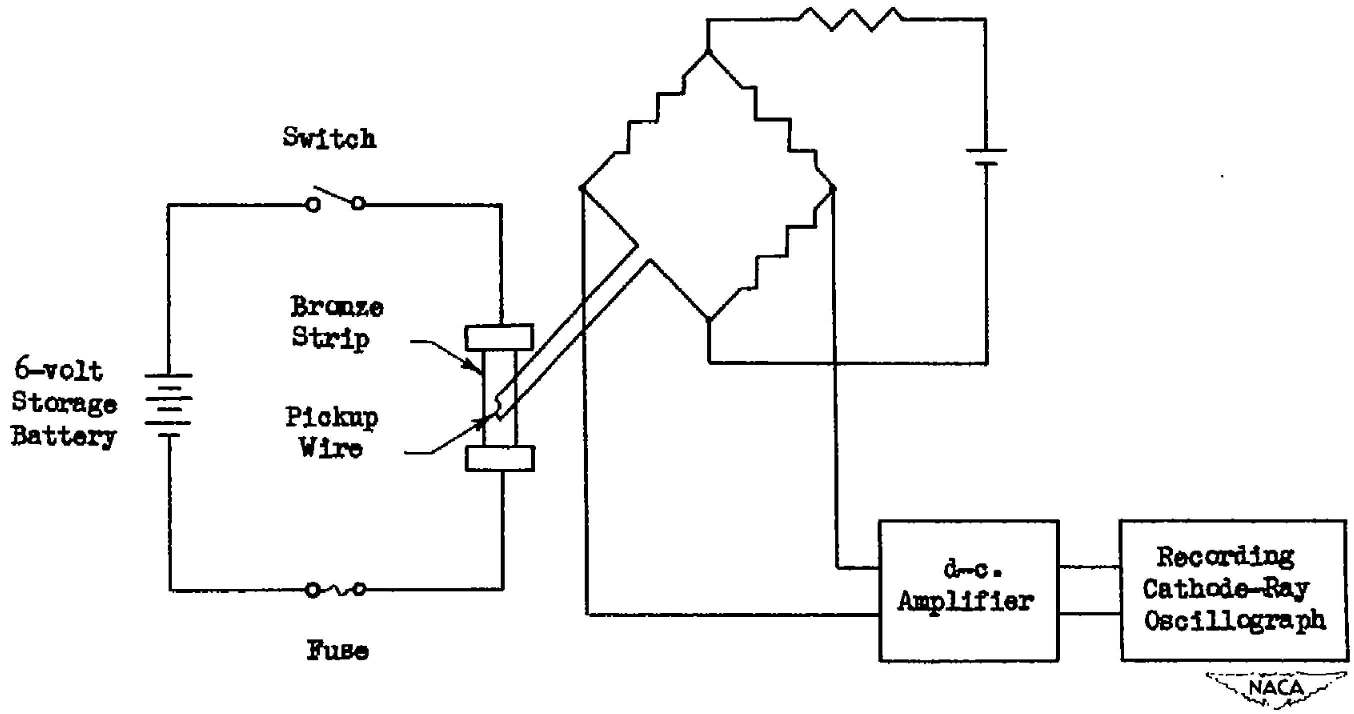

Figure 1.- Schematic diagram of test setup for determining pickup response.

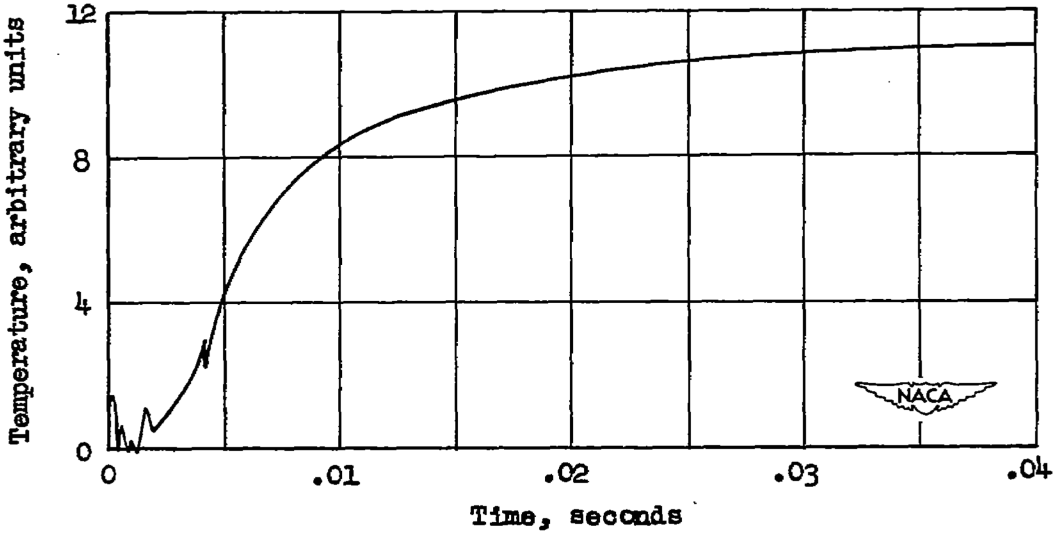

Figure 2.- Dynamic response of an 0.0005-inch pickup wire with two insulating layers of varnish.

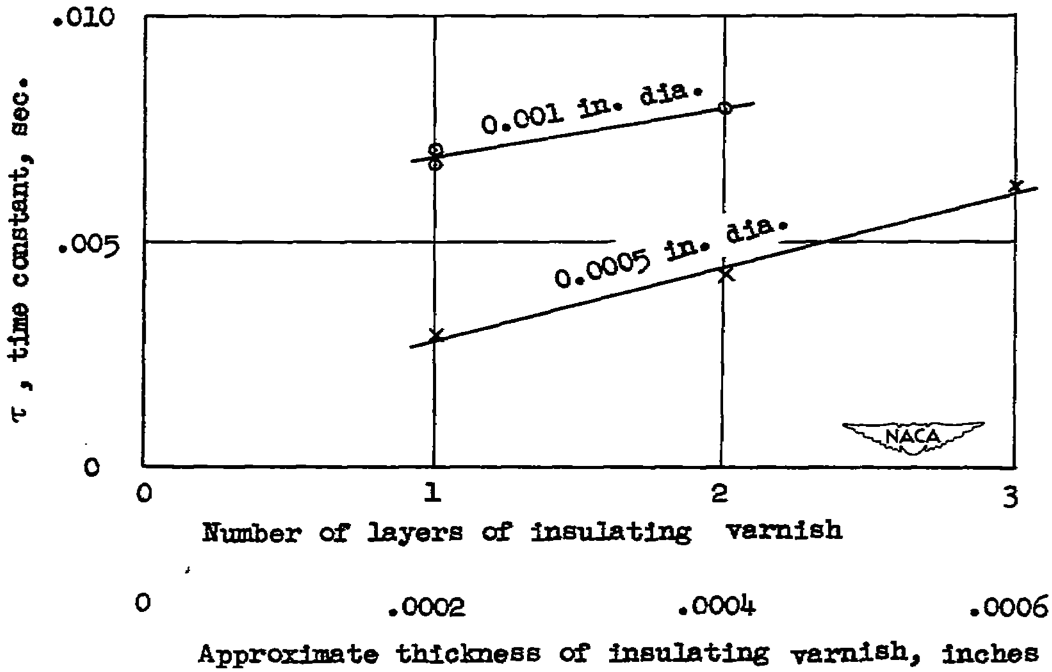

Figure 3.- Variation of pickup time constant with wire size and insulating layers.

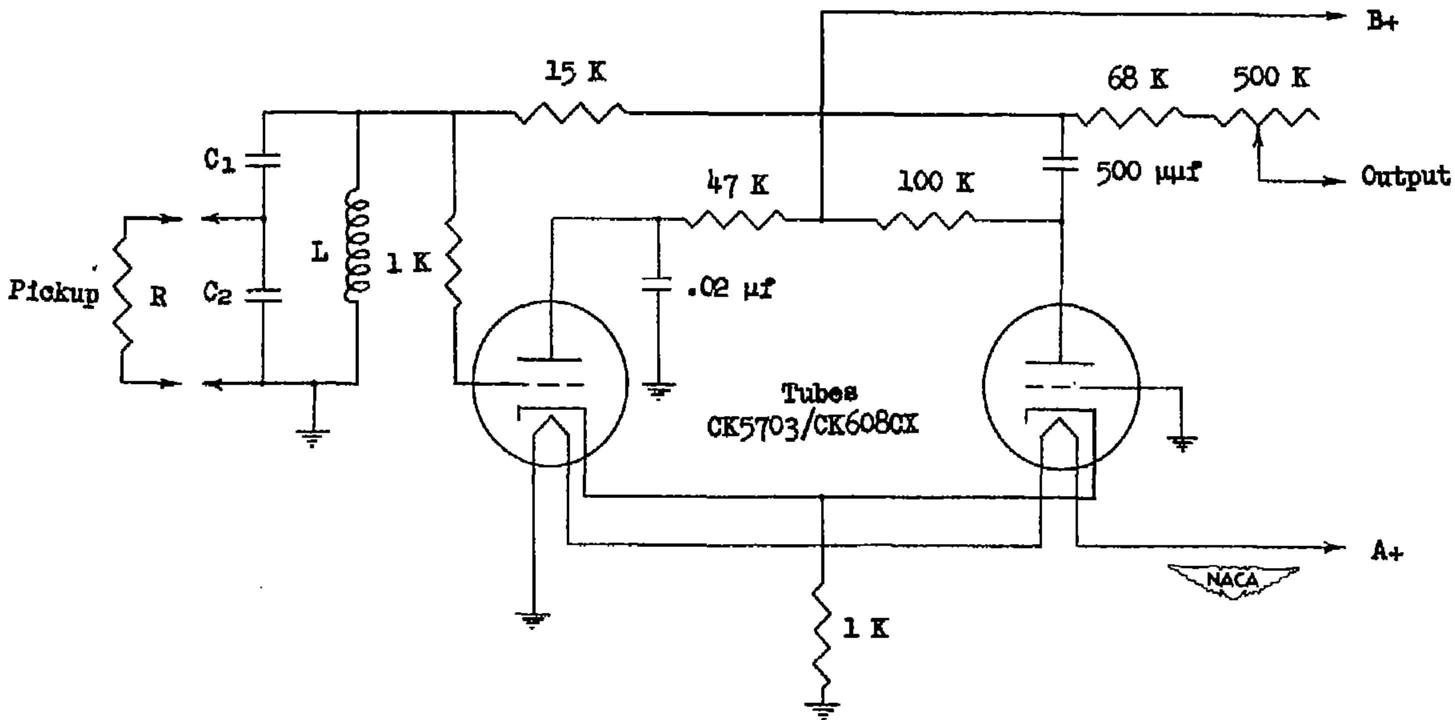

Figure 4.- Schematic diagram of resistance modulated subcarrier oscillator.

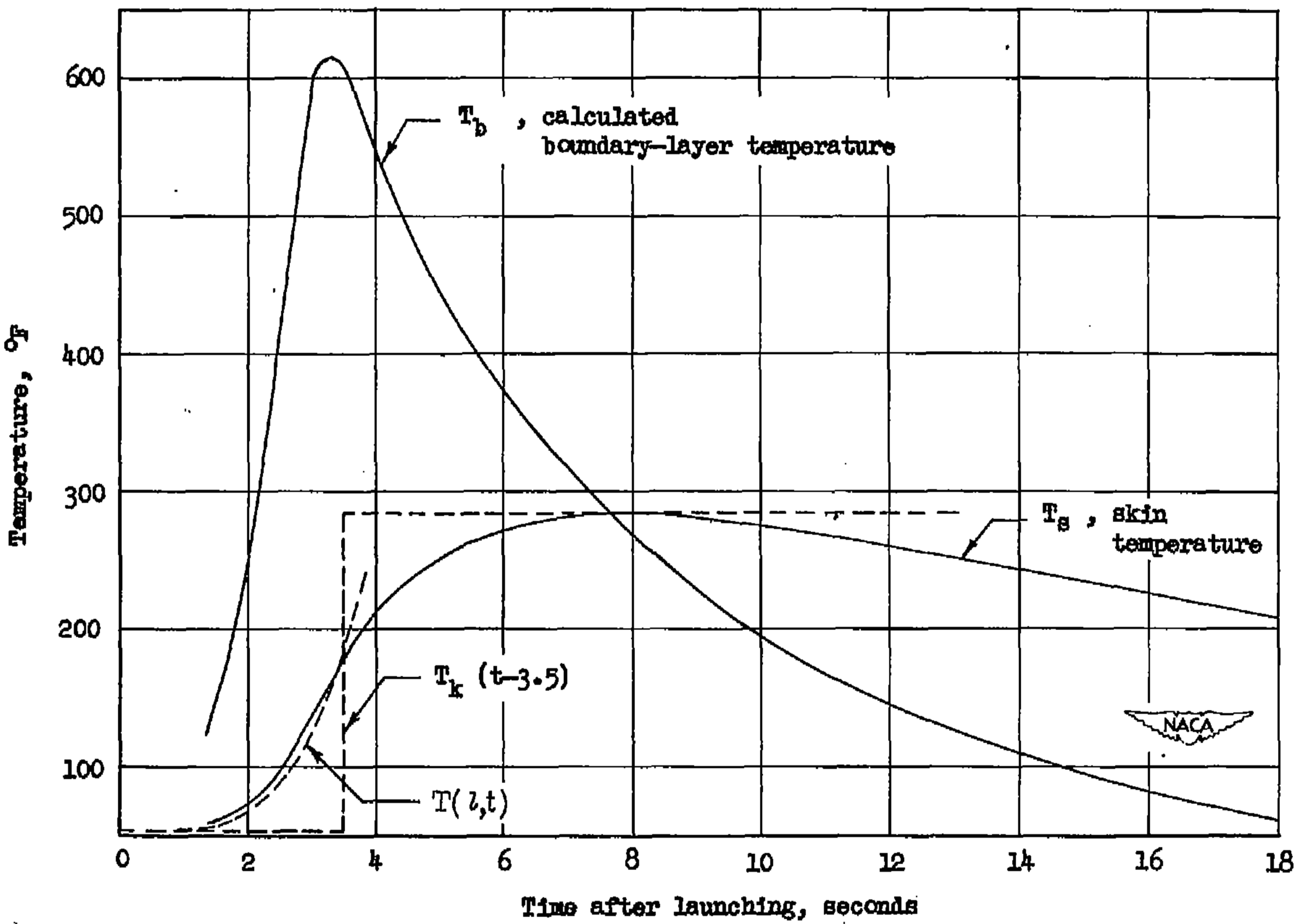

Figure 5.- Skin temperatures telemetered from station 86; calculated boundary-layer temperature; and functions approximating the skin temperature.

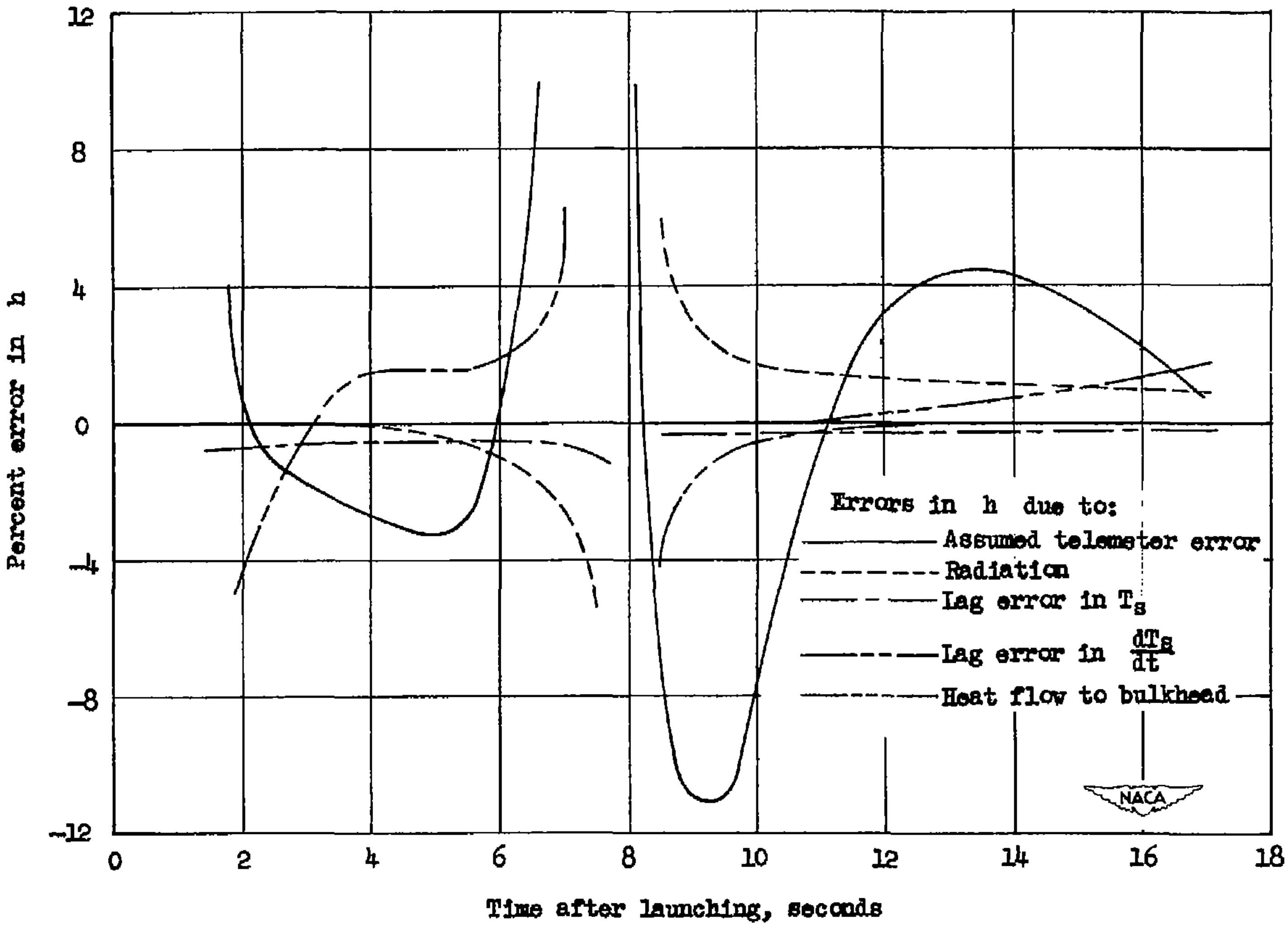

Figure 6.- Percent errors in heat-transfer coefficient caused by various factors.

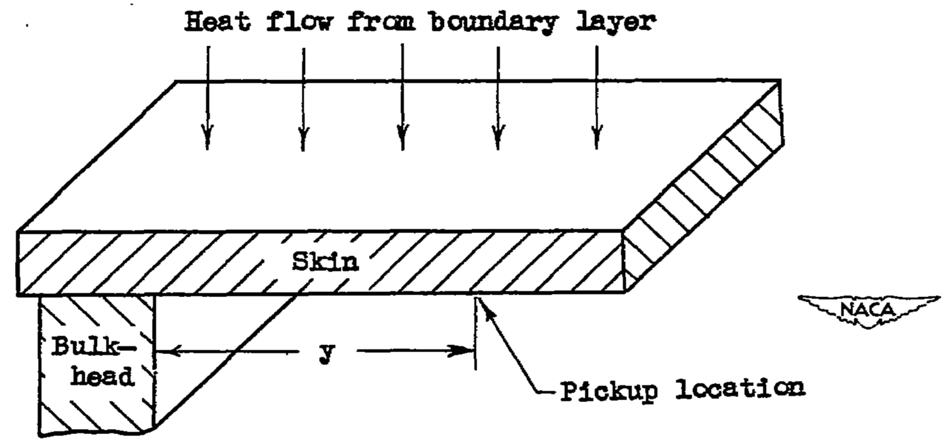

Figure 7.- Sketch showing location of pickup with respect to a bulkhead.

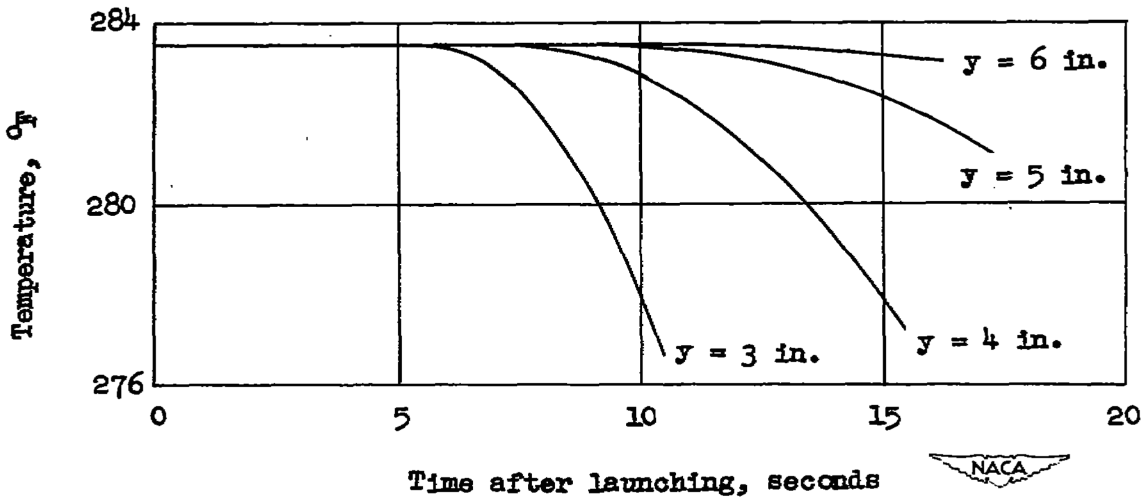

Figure 8.- Skin temperatures in the vicinity of a cold bulkhead for a simplified heating function.

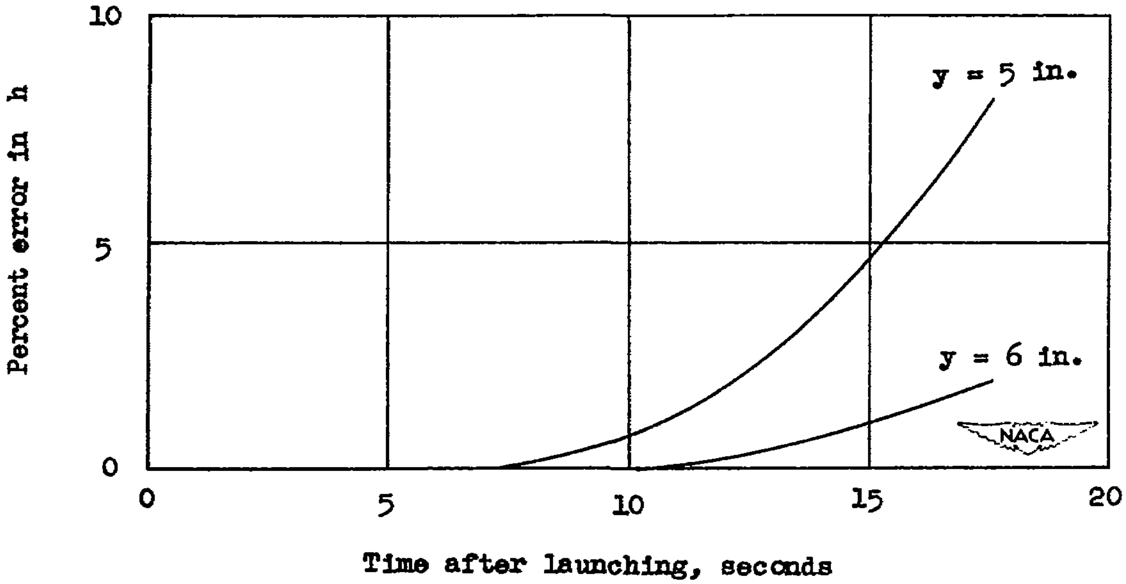

Figure 9.- Error in the determination of heat-transfer coefficient in the vicinity of a bulkhead.

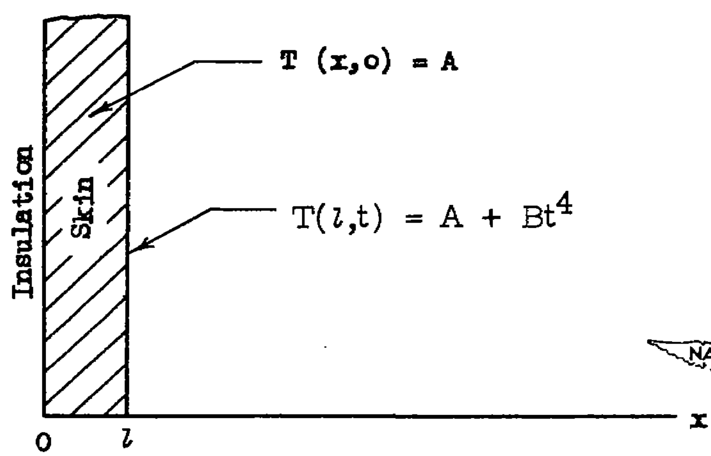

Figure 10.- Sketch showing conditions used for determining the temperature drop through the skin.

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