CONTINUOUS SKIN CONSTRUCTION TECHNIQUE FOR FABRICATING MODELS FOR AERODYNAMIC HEAT-TRANSFER STUDIES INVOLVING VERY SMALL TRANSIENT HEATING RATES

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ABSTRACT

A satisfactory technique has been developed which allows simple or complicated shapes to be heavily instrumented for the purpose of measuring either small or large temperature rises for very short test times during aerodynamic heating investigations conducted in the Langley hotshot tunnel.

The basic technique consists of attaching a continuous thin sheet (0.002 in. thick) to a supporting surface (model body geometry) through which a series of holes of known shape have been drilled. When thermocouple wires (chromel-alumel wires of 0.001-inch diameter) are attached to the thin sheet through the drilled holes, each disk of material serves as an individual calorimeter which is capable of rapid response to sudden but small temperature changes. This method of instrumentation has proven to be a durable and satisfactory technique.

INTRODUCTION

The state of the art for heat-transfer measurements has failed to meet the need in hypervelocity aerodynamic facilities, especially in shock tubes, shock tunnels, and other impulse tunnels. In order to conduct aerodynamic heating investigations in the Langley hotshot tunnel, it was necessary to undertake the development of a suitable technique. Specific requirements were that the measuring device would have rapid response for the 0.100-second tunnel test times, have the capability of accurately sensing less than 1 Btu/ft^2-sec, and be able to survive the temperatures and pressures to be encountered for multiple tunnel tests.

A technique has been developed which has been used successfully on a flat plate at zero incidence, on a cylinder transverse to the stream, and on a rather complicated lifting reentry configuration for angles of attack from 10° to 50°. These tests were made in the Langley hotshot tunnel for a nominal Mach number of 20, free-stream Reynolds number of 30×10^4 per foot, and stagnation pressure and temperature of 12,000 lb/sq in. and 3,000° K. (See ref. 1 for tunnel calibration.) The technique as applied to the cylinder and the lifting reentry configuration is described in this presentation.

SYMBOLS

C	length of model, in.
c	specific heat of sensor material, Btu/lb-°F
E	electromotive force, volts
k	thermocouple gage calibration constant, millivolts/°F
l	sensor thickness, in.
M_∞	free-stream Mach number
$\dot{q}$,Q	local heat-transfer rate, Btu/ft^2-sec
R_∞/ft	free-stream Reynolds number per foot, $\frac{\rho_\infty V_\infty}{\mu_\infty}$
T	surface temperature, °K
T_t	stagnation temperature behind normal shock, °K
t	time, sec
V	free-stream velocity, ft/sec
x	characteristic length, in.
α	angle of attack, deg
ρ	density of sensing material, lb/ft^3
ρ_∞	free-stream density, lb/ft^3
μ_∞	free-stream viscosity, lb/ft^2-sec

REQUIREMENTS AND OBJECTIVES

Transient heat-transfer rates ranging from [redacted] less than 1 to 100 Btu/ft^2-sec are produced in [redacted] hotshot tunnel at nominal test condi- [redacted] R_∞/ft ≈ [redacted]. The [redacted] e tunnel test [redacted] nds. A more detai [redacted] eration and calibration can be found [redacted] e 1. Of interest are very low heating rates, as well as the stagnation heating rates which are somewhat higher, depending on the flow conditions and model geometry. Because no appropriate commercially made, miniaturized, high-response instrumentation was available to measure these low heating rates for short run durations, it was necessary to develop a technique by which nearly instantaneous surface temperature changes with time could be recorded with minimum error. This technique was to be adaptable to both smooth flat surfaces and compound curvatures with small or large radii. From the preceding requirements, it was concluded that high sensitivity and response were needed to record very small heating rates for the very short test times.

In general, it is accepted practice to measure the amount of heat flowing into a solid by determining the rate of change of temperature with respect to time. One accepted method consists of taking a mass of material having a known density, thickness, and area and inserting it into a support surface. With suitable instrumentation, this known mass acts as a sensing element or calorimeter. The rate of change of temperature with respect to time of this sensing element is detected by attaching a thermocouple to the back side of the known material and connecting the thermocouple to suitable recording equipment.

The primary function of the calorimeter is to measure the heating rate that would be present on a surface if the sensor were not present. Therefore, the calorimeter presence must not alter the thermal energy being measured. This requirement imposes restrictions on design, fabrication, calibration, and installation of the gage in order to obtain valid measurements. Many errors can be eliminated by giving proper attention to the preceding requirements and restrictions during development stages.

The energy balance for a thin calorimeter assuming negligible conduction heat loss is

$$\dot{q} = \rho c l \frac{dT}{dt} \tag{1}$$

The change in temperature with time, dT/dt, of the sensing material in equation (1) is detected by a thermocouple which generates an electromotive force proportional to temperature. The change in electromotive force may be expressed as

$$dE = k\ dT \tag{2}$$

where k = constant (millivolts/$^\circ$F). Then by the substitution of equation (2) into equation (1) we get

$$\dot{q} = \frac{\rho c l}{k} \frac{dE}{dt} \tag{3}$$

When equation (3) is written thusly

$$\frac{dE/dt}{\dot{q}} = \frac{k}{\rho c l} \tag{4}$$

it can be seen that the sensitivity, $\frac{dE/dt}{\dot{q}}$, is inversely proportional to the thickness l since k, ρ, and c are essentially constant for a given choice of sensor material.

In order for the reduced sensing-surface thickness to be effective, the thermocouple wire diameter necessarily needed to be less than or at least no greater than the surface thickness. (See ref. 2.) Preferably, the diameter should be less than the thickness. Furthermore, the wire length should be held to a minimum to reduce lead length resistance.

In selecting a sensing material for making the desired heating rate measurement, it was necessary to consider the temperature rise of the material mass during the tunnel run time. The temperature rise was dependent upon the heat rate which was to be measured, the run duration, and the material thickness. Therefore, the following limitations were placed on the materials to be used in the sensor:

(1) The calorimeter was to be constructed so that the anticipated temperature rise would not exceed that of the working limits of the sensing material, bonding material, or support structure.

(2) The ratio of the sensing disk radius to thickness was made large to prevent heat losses radially outward of the material sensing area.

(3) The calorimeter needed sufficient sensitivity to produce an electrical signal which could be recorded with accuracy.

In areas where the temperature rise was expected to be somewhat larger than elsewhere, thickness of the sensor material could be increased. For instance, the material would need to be much thicker at the stagnation region, depending upon the associated temperature rise, than on the leeward side of the model.

CONSTRUCTION TECHNIQUE

The preceding requirements and objectives were partially fulfilled in the initial applications of the calorimeter technique for the construction of plug or capsule-type transducers. These were similar to those of references 3 to 6. These gages contained a disk of sensing material with a chromel-alumel thermocouple welded to the rear surface; the disk was supported at its perimeter by a nylon insulator, and this assembly was installed inside a steel case to which larger diameter wires were attached. The gages were then installed in holes within the surface being tested in such a manner as to present a smooth contour with the surrounding area by mounting the calorimeter flush with the surface. (See fig. 1.)

Experiences in construction and testing with these capsule-type calorimeters proved to be unsatisfactory, especially when numerous gages were to be used in a model of complicated design. A considerable amount of labor was necessary to construct and assemble the many individual parts so as to produce a satisfactory gage of reliable characteristics. The size and shape of these gages limited the number and location of instrumented points that could be obtained on a model. These gages could not be mounted in areas of small radius without causing a disturbance to the flow.

In order to alleviate the previously discussed problems with the individual calorimeters, additional effort was expended to develop a simplified, more uniform method of measuring multiple low heating rate readings simultaneously over a given surface area for very short durations.

Thin sheets of No. 302 stainless steel, 0.002-inch-thick, and 0.001-inch-diameter chromel-alumel thermocouple wires were selected as the basic sensor material and thermocouple elements. Selection of this combination was based on several factors. Experience indicated that the chromel-alumel wires would stay fastened to the stainless steel after being subjected to a large number of tests. The combination of stainless steel and chromel-alumel proved to be very durable and produced sufficient sensitivity to record the output signal with accuracy.

The elements composing the basic final design are shown in figure 2, which is a schematic of the technique. The structure support is simply that of the model, which may be either flat or curved.

A suitably shaped model for supporting the skin to be used is first made and the gage-hole locations are machined through the support surface. The model exterior surface is then smoothed and, if necessary, polished. The thin skin is then stretched and bonded to the support surface. The bonding material is a clear elastomeric film similar to double-back tape and is 0.001 inch thick. Under proper temperature and pressure control, the thin skin can be smoothly bonded to the support surface without dimpling effects at the gage-hole locations or elsewhere. Spot welding of the thin skin to the support surface also has proven to be satisfactory.

It becomes very important to know, with accuracy, the thickness, density, and specific heat of the sensor material, especially when small temperature changes are involved. Thus, this technique takes the form of attaching a continuous thin sheet of a material having previously determined characteristics to a supporting surface through which a series of holes of known diameter have been previously made. Each perforated area, having a known material stretched across it with thermocouples attached to the under surface of this material, serves as a plug-type calorimeter but with a more uniform surface. The successful application of this concept depends on the ability of the experimenter to attach over the top of the perforated mountings, sheets or "skins" of metal thin enough to give the desired sensitivity. For short test times (on the order of milliseconds) and for low to moderate heating rates (1 to 25 Btu/ft^2-sec) the temperature rise would be very small and therefore the sensing material thickness need be on the order of 2 mils.

The thermocouples were constructed from commercially manufactured 0.001-inch-diameter chromel and alumel wire. Fastening the small thermocouple wires to the thin skin was attempted by two methods, electron beam welding and spot welding. Electron beam welding proved unsatisfactory because it was difficult to control and either resulted in a ball at the junction or a void in the skin, both undesirable conditions. Furthermore, the electron beam welding proved to be costly and time consuming because of "jigging" and evacuation of the working chamber. Satisfactory results were obtained by spot welding the two wires to the back surface. Considerable effort was expended experimentally toward obtaining the proper voltage and pressure settings on the welding instrument to obtain good results in terms of securing the wires so as to avoid the undesirable factors mentioned for the electron beam welding.

The chromel-alumel wires were held to a short length (0.25 in.) in order to reduce lead resistance. Number 30-gage copper lead wire was connected to the chromel-alumel wires to extend the leads to the recording instruments. Since a small temperature rise for such a short run duration was expected, the copper leads and thermocouple connections served as a cold junction.

Figure 3 is a schematic of the instrumentation and data system used to record and calibrate the output of the transducers. The lead wires were connected to a commercially built emf calibrating unit, which allowed a step input of a known voltage to be applied to each channel of data. The voltage could be controlled very accurately. An oscillograph recorder, in conjunction with the calibrating unit, recorded the output with time both for calibration and tests. A linear calibration of millivolts as a function of deflection in inches for each channel of data was determined.

It was further desirable to calibrate these gages with pulses of known heating rates. A heat-transfer calibrating unit has been designed and constructed. This unit produced low heating rates from 1 to 20 Btu/ft^2-sec with good repeatability and allowed a dynamic pulse of known heat rate to be applied to a gage to be calibrated. (See fig. 4.) The calibrating unit consists of a heater coil and attached blower. A nozzle was designed and used to reduce the airflow across the heater coil from 1.5-inch- to 0.5-inch-diameter cross section. The inside of the nozzle is highly polished and is provided with a mixing screen and radiation shield. A 6-inch-diameter slotted disk is mounted on a spring-loaded shaft and in line with the nozzle (plane of disk normal to nozzle flow). The disk is insulated so as to reduce heat input from the disk to the gages under calibration. The disk, after being wound on the spring loaded shaft, can be rotated by a trigger release or may be rotated by hand. When the slot on the disk coincides with the hot airstream from the nozzle, a step input of heat is imposed upon the face of a gage to be calibrated. A standard calorimeter is used in place of the calibrated gages to determine the output of the airstream. This calorimeter consists of a copper slug of known mass, from which heating rates of the airstream can be determined by recording the temperature rise of the copper slug versus time.

The exit airstream from the nozzle has been temperature surveyed across the diameter and down the length. The airstream has been found to be uniform in temperature across the core and down the length for approximately 2.5 inches.

APPLICATION OF TECHNIQUE TO MODELS

In principle, the same technique can be applied to complicated geometries as for flat surfaces. The most severe problem arises in shaping and bonding the thin skin to more complicated shapes. Small curvatures and irregular surfaces produce most of the problems, especially if the curvatures are three dimensional.

Cylinders

The 1-inch-diameter, 10-inch-long cylinder in figure 5 was constructed by first drilling 1/4-inch-diameter holes along the stagnation line. A continuous stainless-steel thin skin (0.004 inch thick) was then wrapped around and bonded to the cylinder. Then 0.001-inch-diameter chromel-alumel thermocouple wires were spotwelded to the underside of the thin skin forming calorimeter gages. The model contained 19 calorimeters and was used to determine enthalpy distributions across the test section of the Langley hotshot tunnel at zero incidence.

Figure 6 presents the experimental and theoretical cylinder stagnation-line heating-rate distribution. The stagnation-line heating is shown as a function of distance from tunnel center line. Stagnation temperature and pressure for the tests were about 2,500° K and 10,000 psi. It may be seen that the theoretical predictions of the heating rate across the flow core (approximately 9 in.) are in good agreement with the experimental results.

Reentry Configuration

The reentry configuration presented in figure 7 is complicated in design, since compound curvature was employed for a basic delta planform configuration. The anticipated rate of heat flux would vary considerably over the entire model from large to very small values, depending upon the test conditions and angle of incidence to the flow. Therefore, the technique of measuring these values on the body at the same time becomes even more difficult than was previously indicated.

Two basic models of the type in figure 7 were constructed in two parts. One was made by casting a fiber-glass model in a mold in two separate halves. A second was made by forming a 1/64-inch-thick stainless-steel model by use of a mold. A female mold was used in conjunction with a male mandrel for both the fiber-glass and the steel models. Holes were then drilled in both models as shown in figure 8(a), where the heat-transfer rate was to be measured. The two halves were constructed in such manner that later they could be joined uniformly to produce a fully sealed configuration, solid in appearance (fig. 8(b)). The interior area was left hollow to allow attachment of thermocouple wires and lead wire extensions (fig. 8(c)). Thin skin sections (0.002 and 0.004 in. thick) were then formed in molds to the exterior shape of the model. The thin skin material was first annealed and then vacuum pressured into the female mold by a male mandrel. The resultant thin skin sections took the form of the reentry configuration. The thickness was checked for uniformity with a micrometer throughout the surface of interest near the gage locations. The thickness was found not to vary in the flat areas, but varied about 1 percent maximum across the curved area.

The thin skin sections were then attached by spot welding the skin to the steel model or by bonding the skin with a contact cement to the fiber-glass model. In both cases, thermocouple wires were attached to the underside of the thin skin, through the machined holes forming the calorimeter. The model halves were then fastened together to form the final instrumented model.

Figures 9(a) and 9(b) are drawings showing the gage locations on the reentry configuration. The circles indicate a single gage location. The entire model has 71 thermocouples. Gages were located along the lower and upper surface center line and in a spanwise direction at seven chordwise stations (stations 1, 2, 4, 6, 7, 7.5, and 8 in.), on the upper and lower surfaces of a single flap, and on the tail fin sides and leading edge.

Typical data traces for two of the thermocouples on the reentry configuration are shown in figure 10. One gage was located near the stagnation point on the nose with a skin thickness of 0.004 inch. The thermocouple sensitivity in this case is 89.1° F/in. The temperature rise is seen to be on the order of 3° F per millisecond. Also shown is a trace representing a gage (0.002 in. thick) located on the upper surface in a very low heating area. The temperature rise here is seen to be on the order of 0.5° F per millisecond. Note that gage sensitivity was large enough so that no amplification was necessary.

Figure 11 is a representative heating-rate distribution for the upper and lower surfaces of the reentry configuration. The angle of attack was 30° and the free-stream Mach number was 20 for a stagnation temperature of about $3{,}000^{\circ}$ K. The experimental data are presented in the form of ratio of local heating rate to that of the calculated stagnation-point heating rate on a sphere at the same test conditions and having the same diameter as that of the leading edge of the reentry configuration. This figure represents the wide range of heating rates measured, ranging anywhere from being equal to the stagnation value on the sphere to about 0.01 that of the sphere value. The data on the flaps, tail fin, and in the spanwise direction were measured but are not presented herein.

Some preliminary tests at low angles of attack were made with the fiber-glass model with attached continuous skin, which gave very similar heating-rate results to those obtained for the steel model. (See fig. 11.) However, the contact cement used to attach the continuous skin on the fiber-glass model proved unsatisfactory when the model was at large angles of attack, and after several repeat tests resulted in dimpling of the gages subsequently producing errors in the heating results. At the present, it has not been determined whether the choice of the cement or the application was in error.

CONCLUSIONS

A technique has been developed which allows simple or complicated shapes to be heavily instrumented for the purpose of measuring small or large temperature rises for very short test times during aerodynamic heating investigations conducted in the Langley hotshot tunnel. The application, calibration, and data handling techniques as well as experimental results obtained on cylinders and on a complicated reentry configuration indicated the following conclusions:

(1) Application of the continuous "thin skin" technique appears to be a satisfactory and efficient method of heavily instrumenting complicated shapes and should be applicable to other impulse hypervelocity facilities.

(2) Construction methods and control of the sensing material properties, such as sensitivity, specific heat and thickness are believed to be an improvement over other means of instrumentation such as "plug" type calorimeters.

(3) Gage sensitivity is large enough that amplification of the thermocouple output is unnecessary.

(4) Experimental results obtained on a transverse cylinder during heat-transfer studies using the present technique compared favorably with theoretical results.

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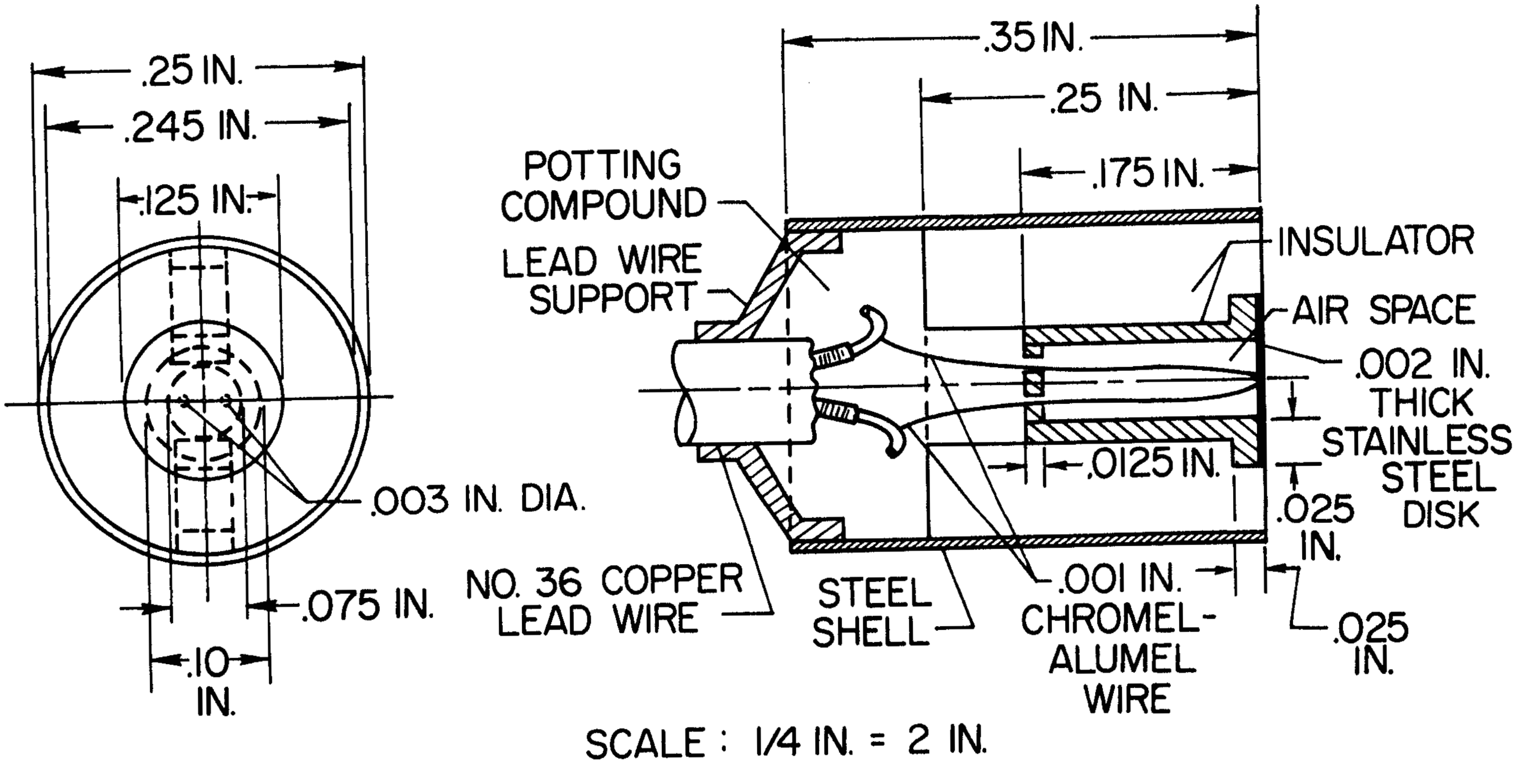

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Figure 1.- Capsule-type calorimeter.

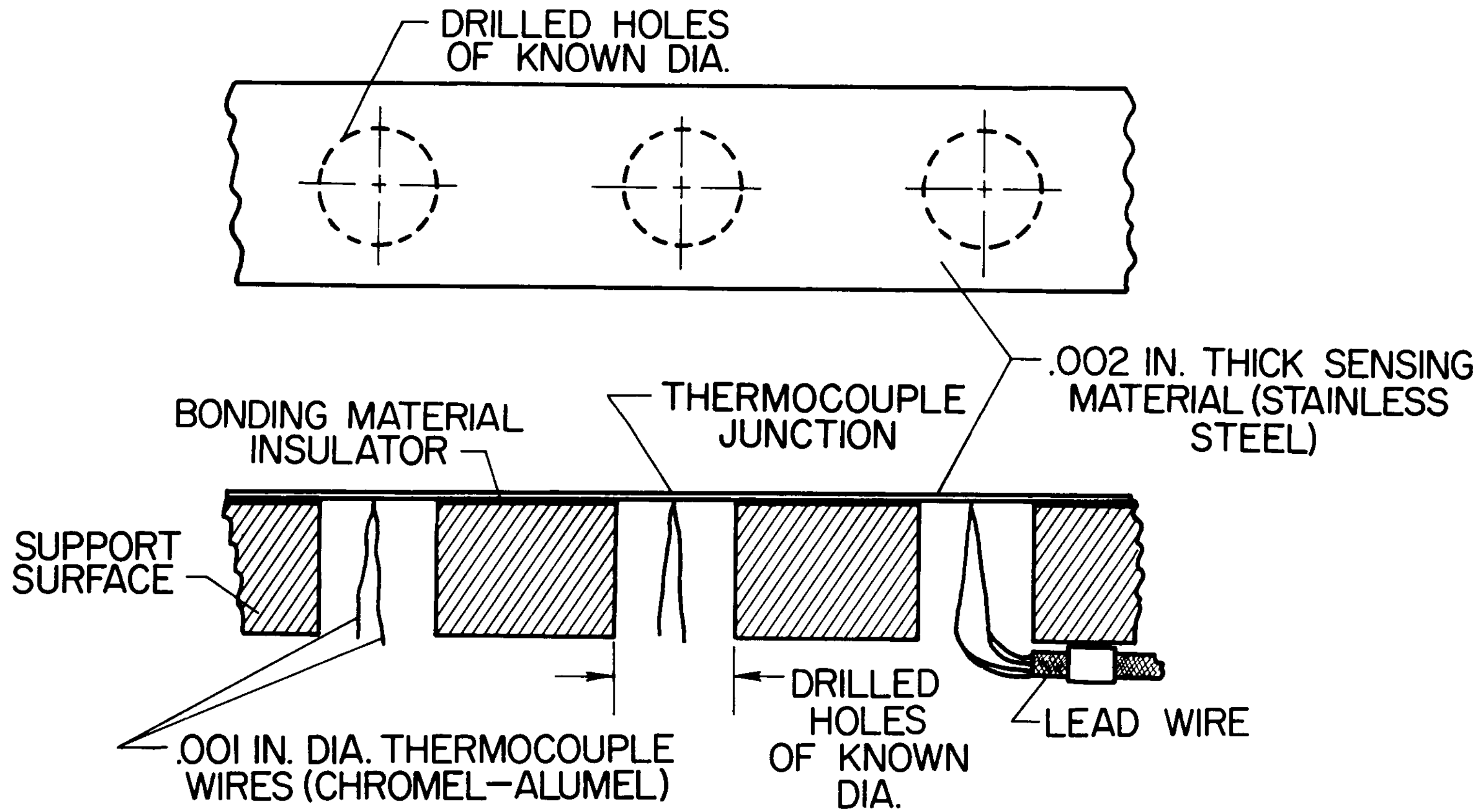

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Figure 2.- Thin skin construction technique.

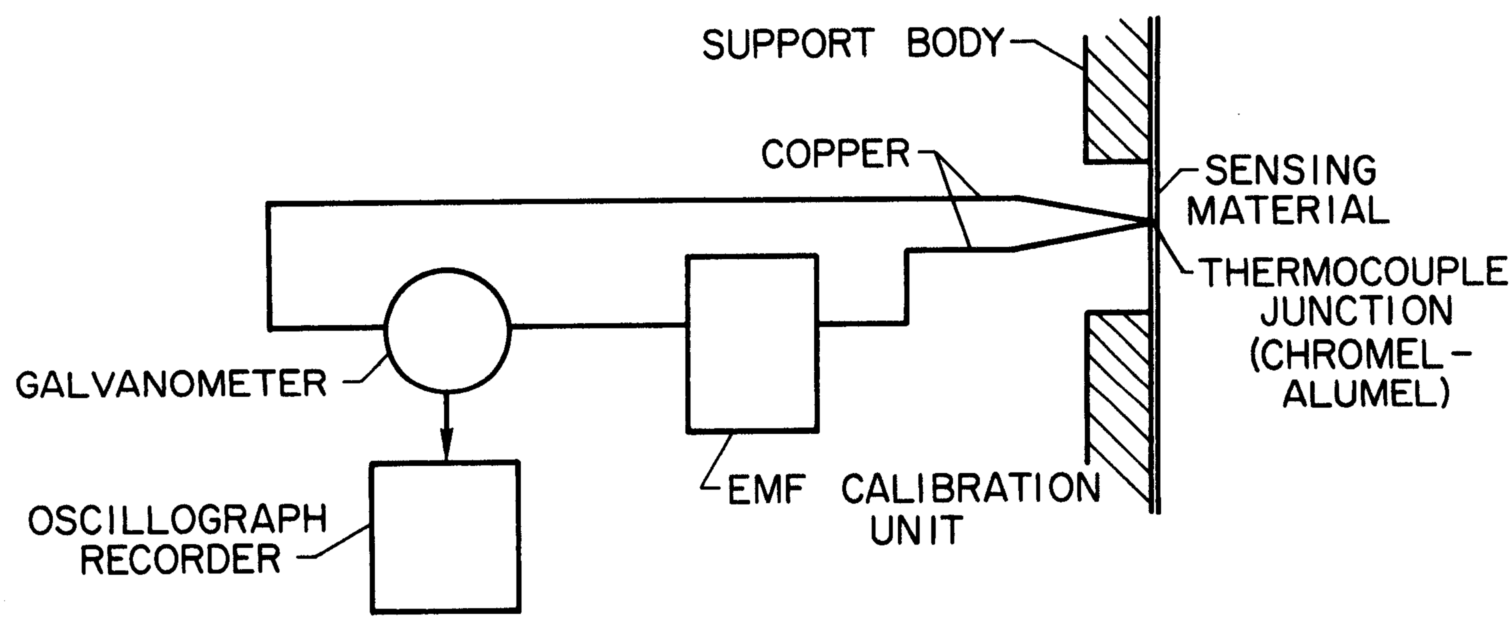

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Figure 3.- Instrumentation and data system.

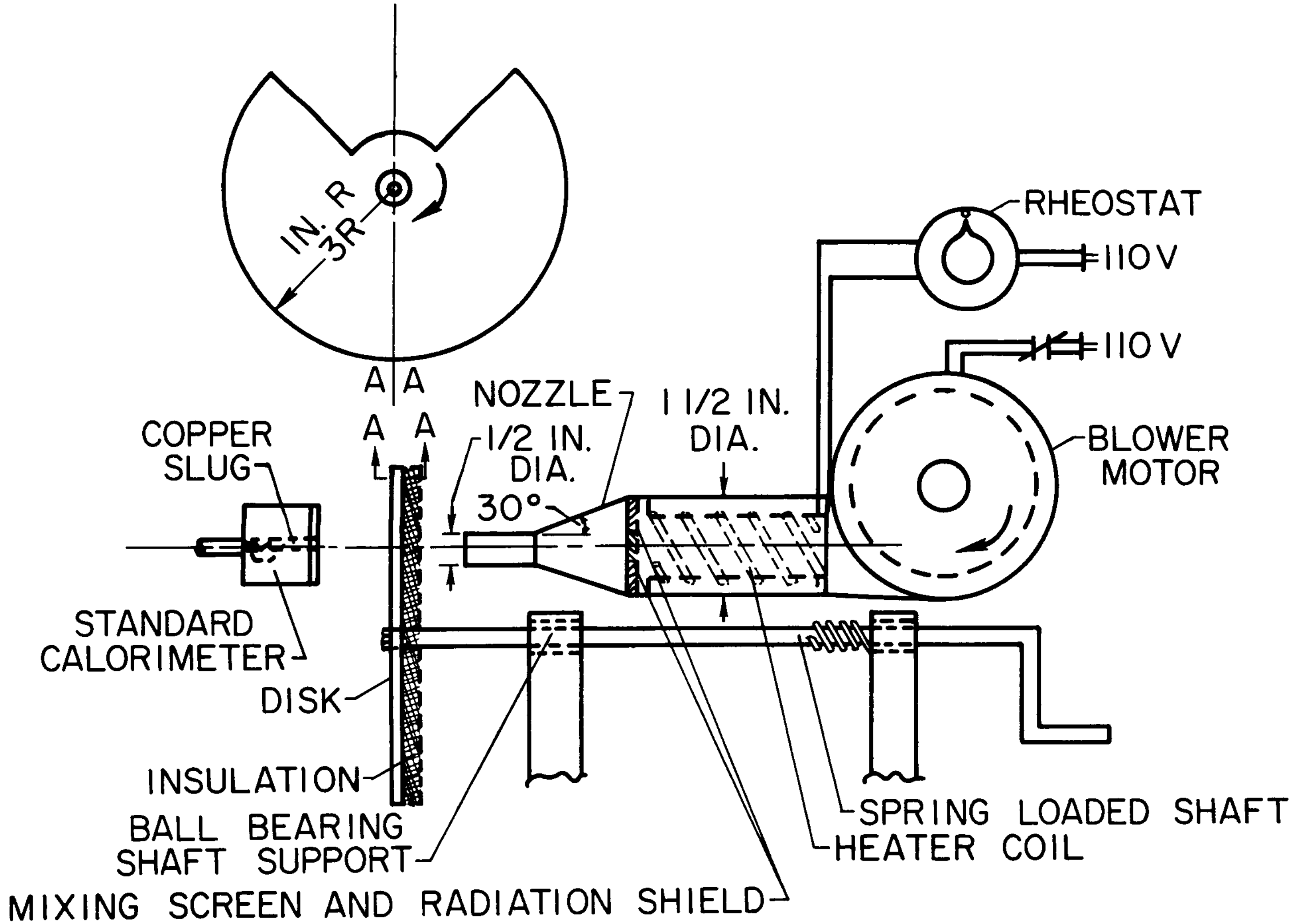

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Figure 4.- Heat-transfer calibrate unit.

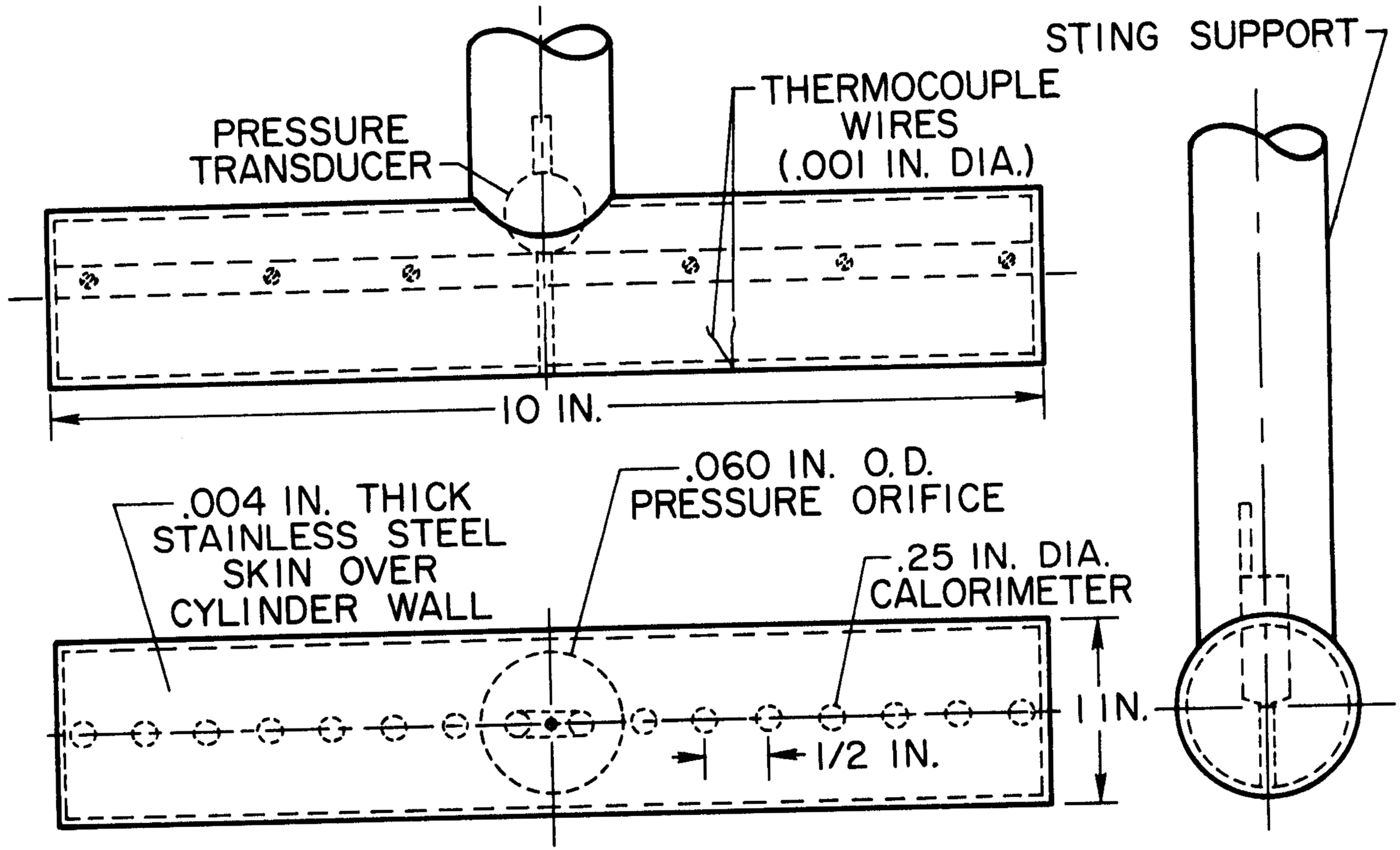

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Figure 5.- Instrumented cylinder for enthalpy distribution measurements.

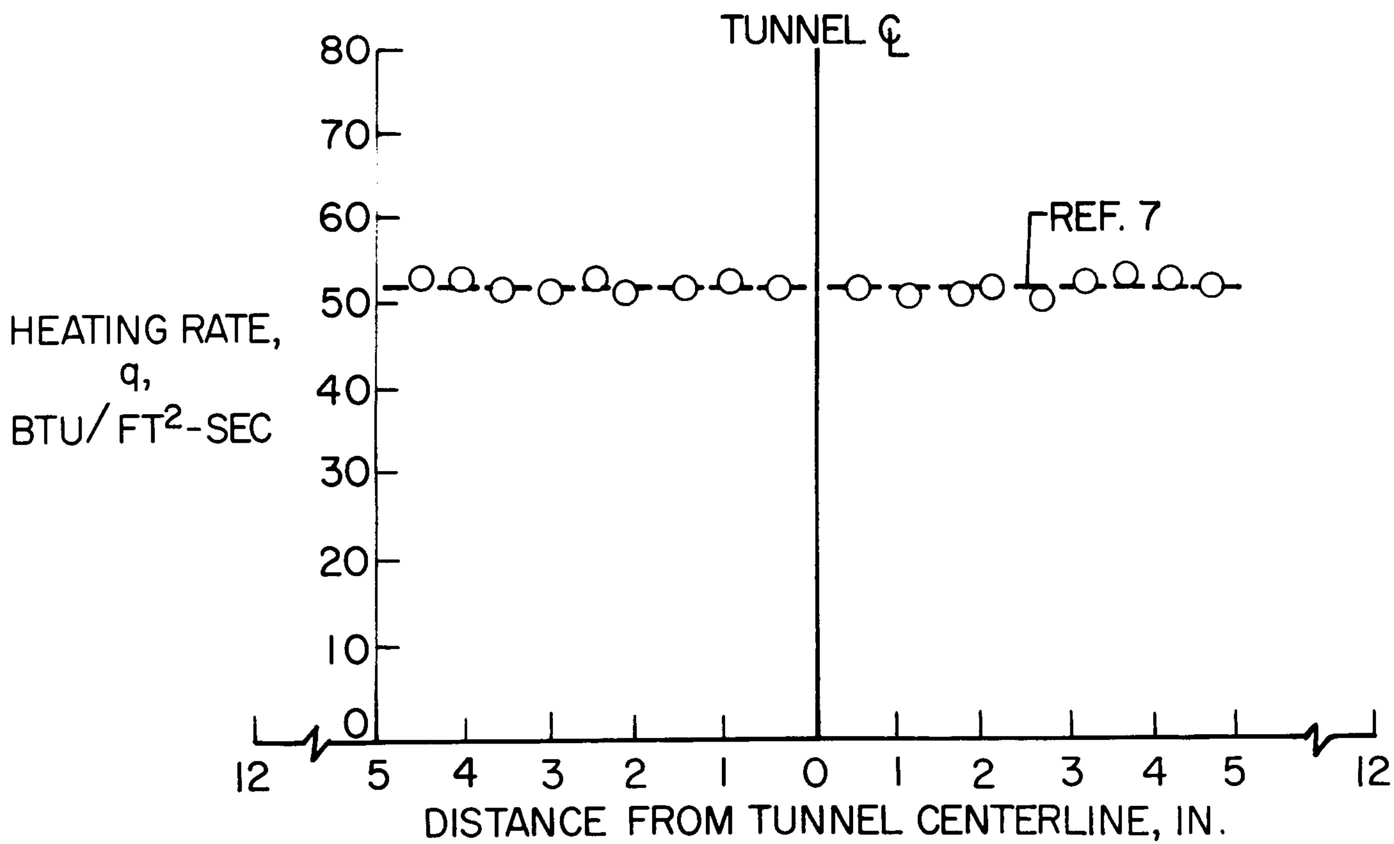

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Figure 6.- Cylinder stagnation line heating-rate distribution.

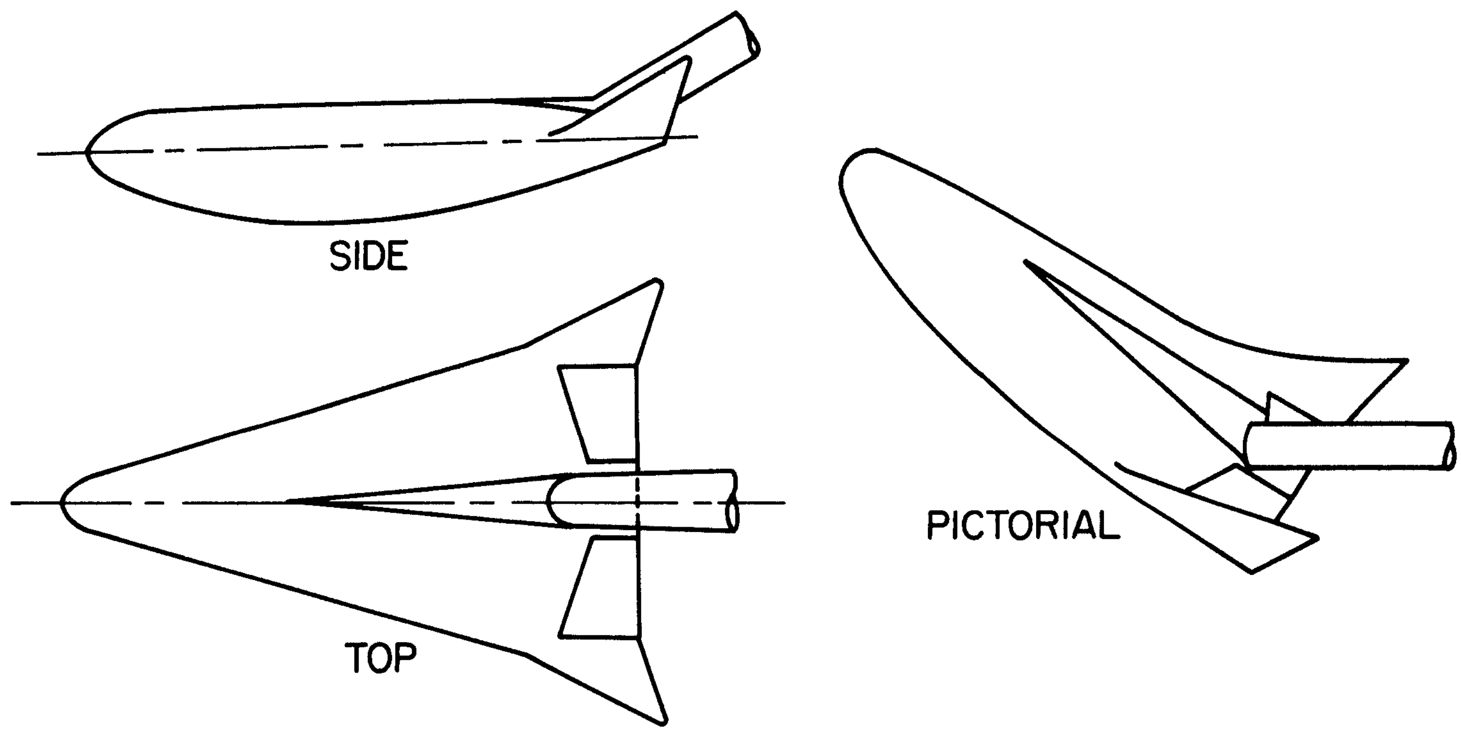

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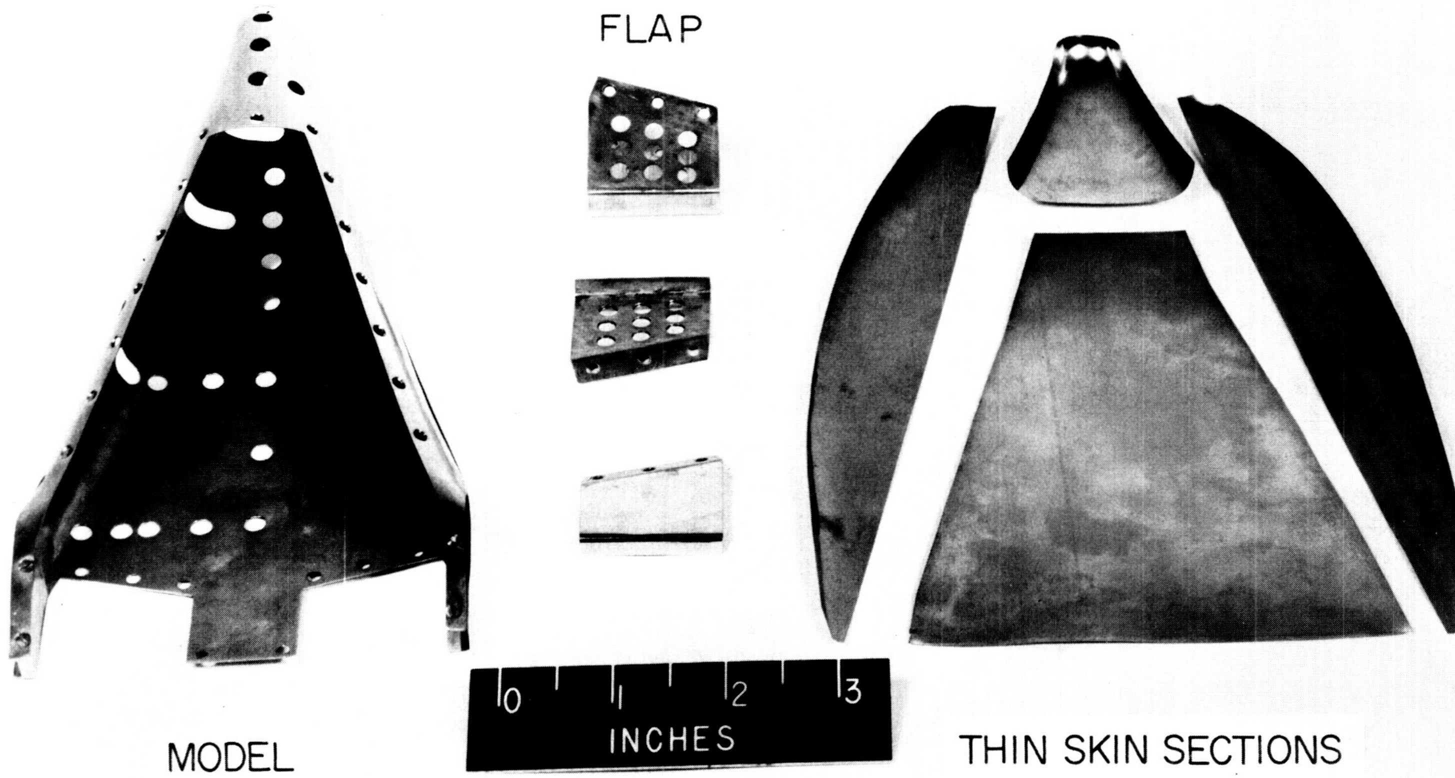
Figure 7.- Lifting reentry configurations.



(a) Components.

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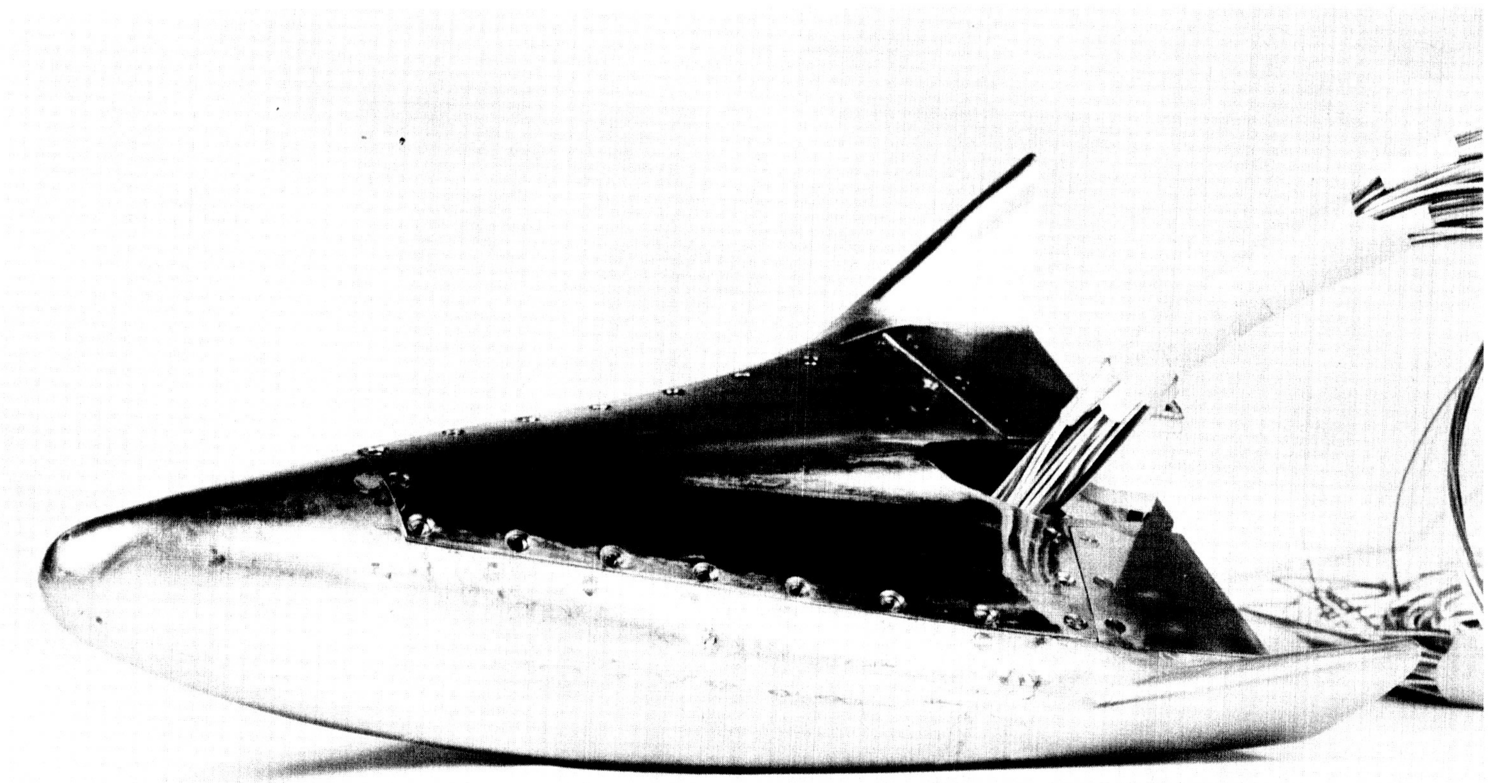
Figure 8.- Reentry configuration.



(b) Side view, hatch closed.

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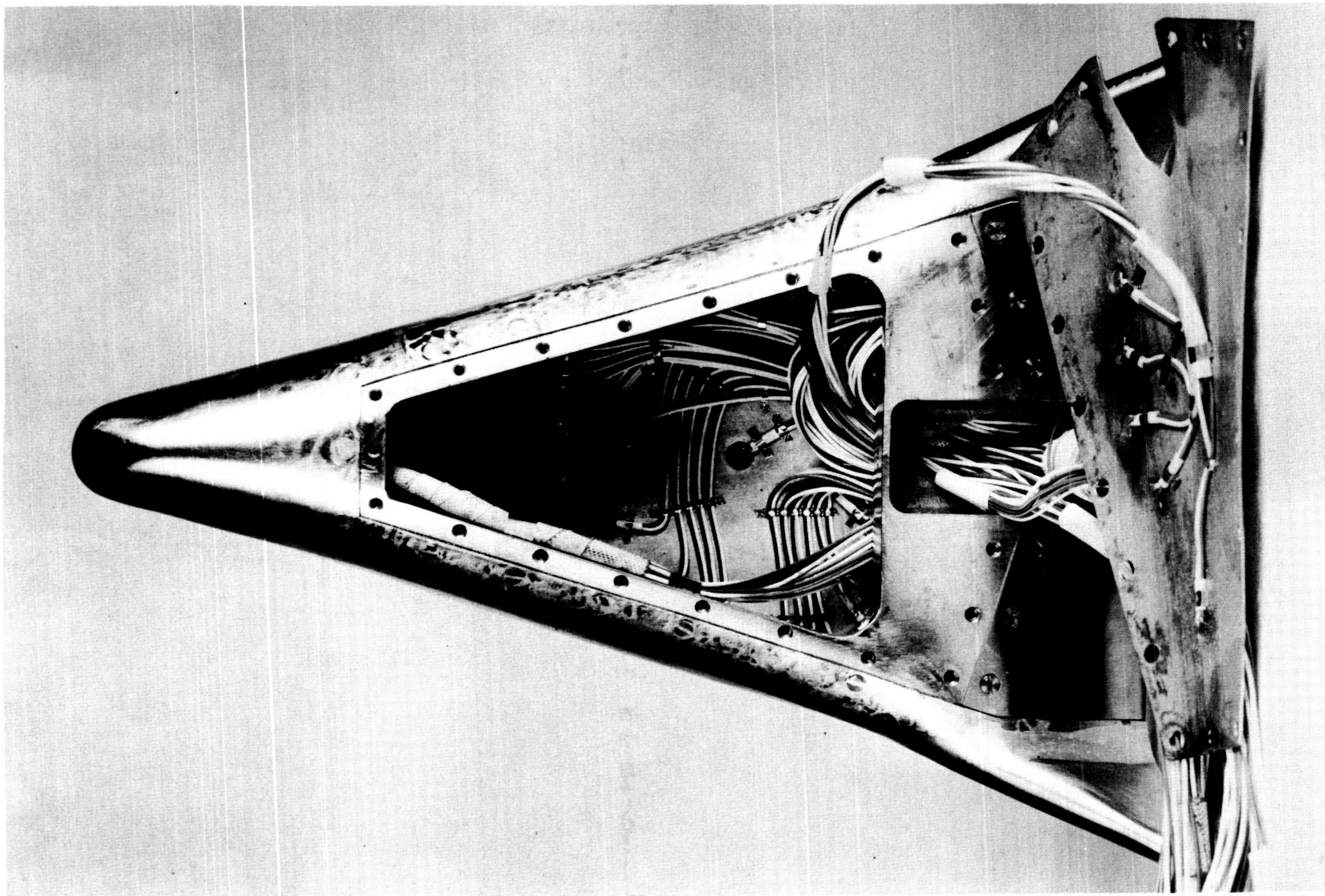
Figure 8.- Continued.



(c) Top view, hatch open.

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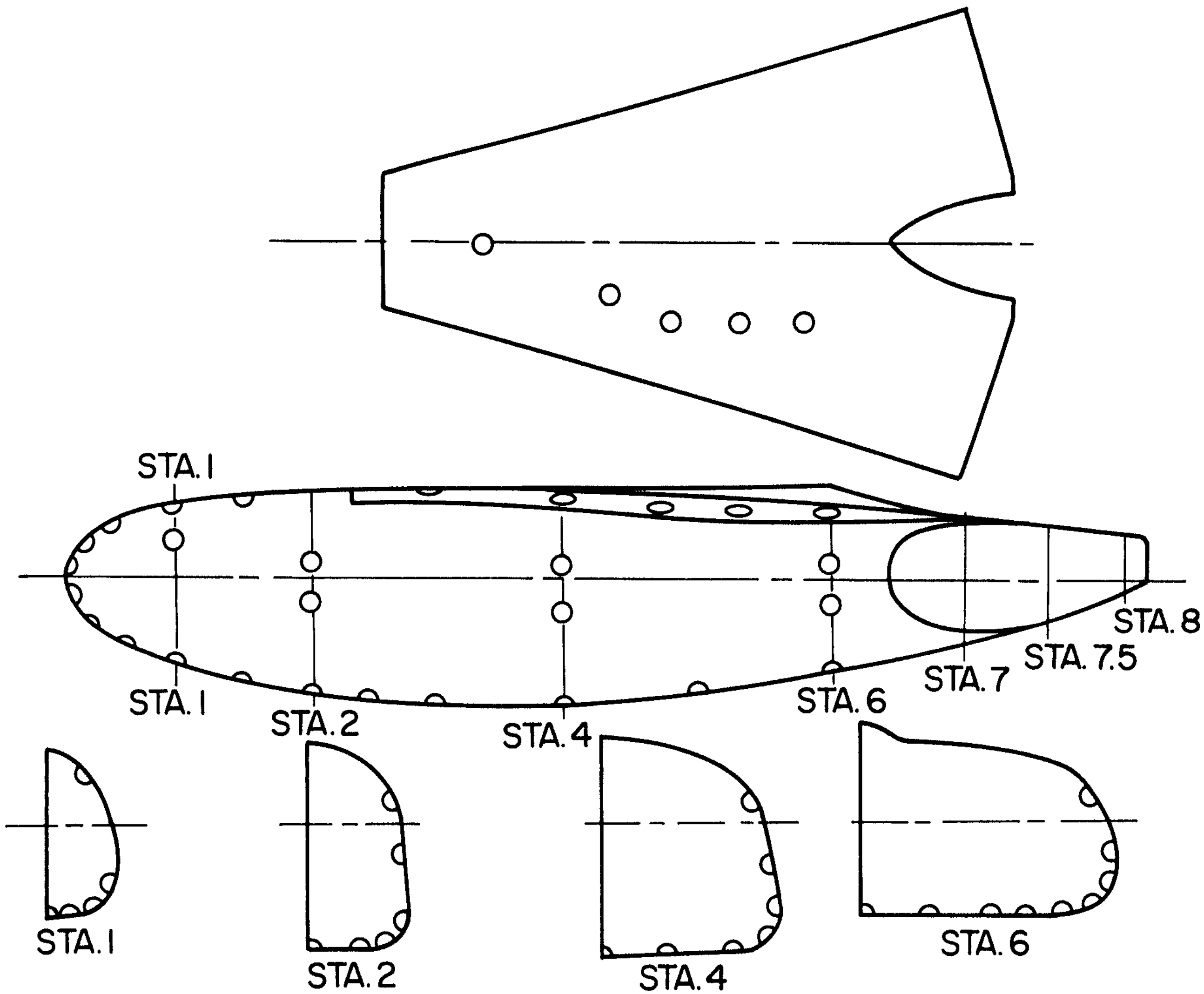
Figure 8.- Concluded.



(a) Main body.

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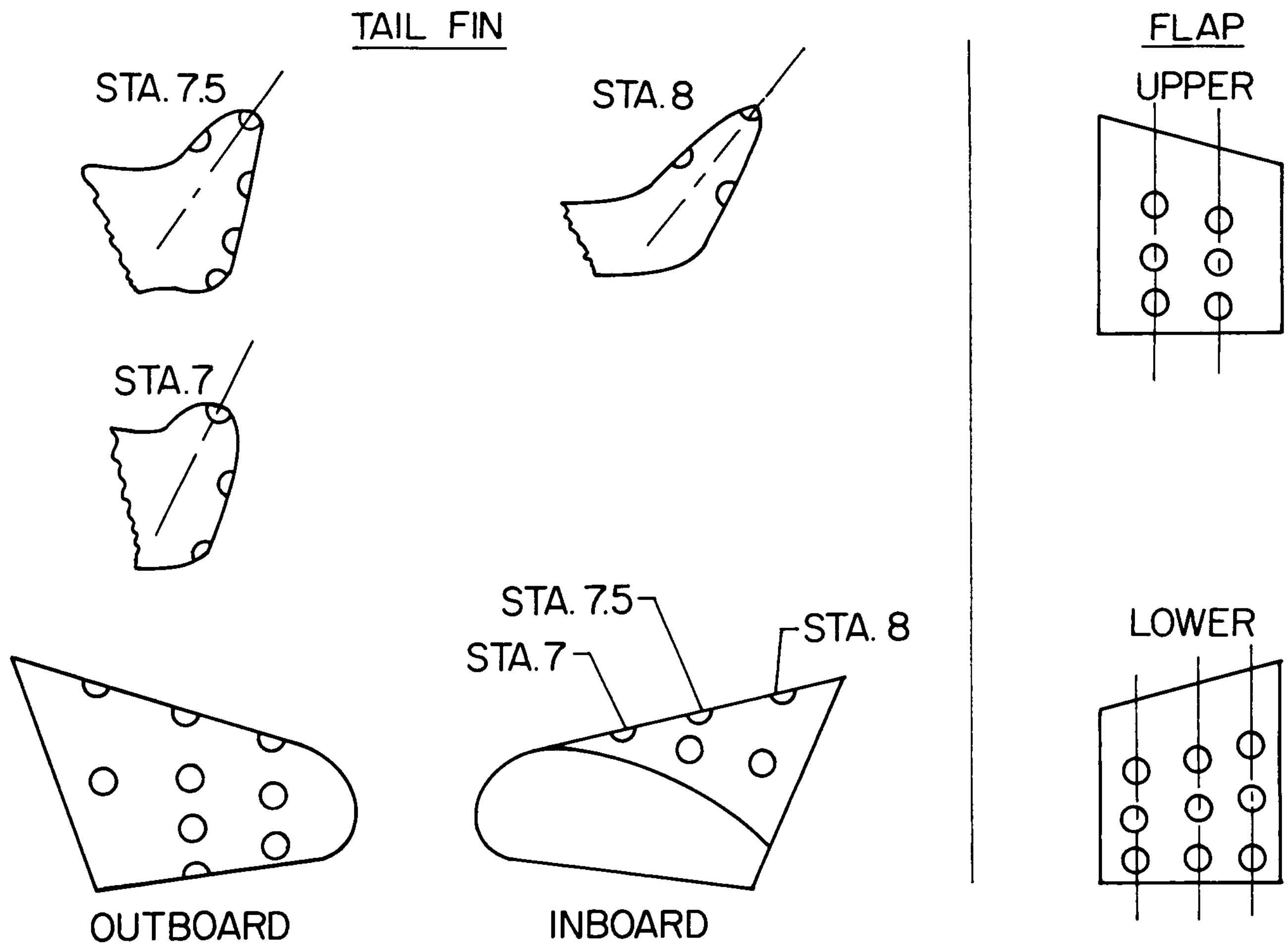
Figure 9.- Thermocouple locations on reentry configuration.



(b) Tail fin and flap sections.

Figure 9.- Concluded.

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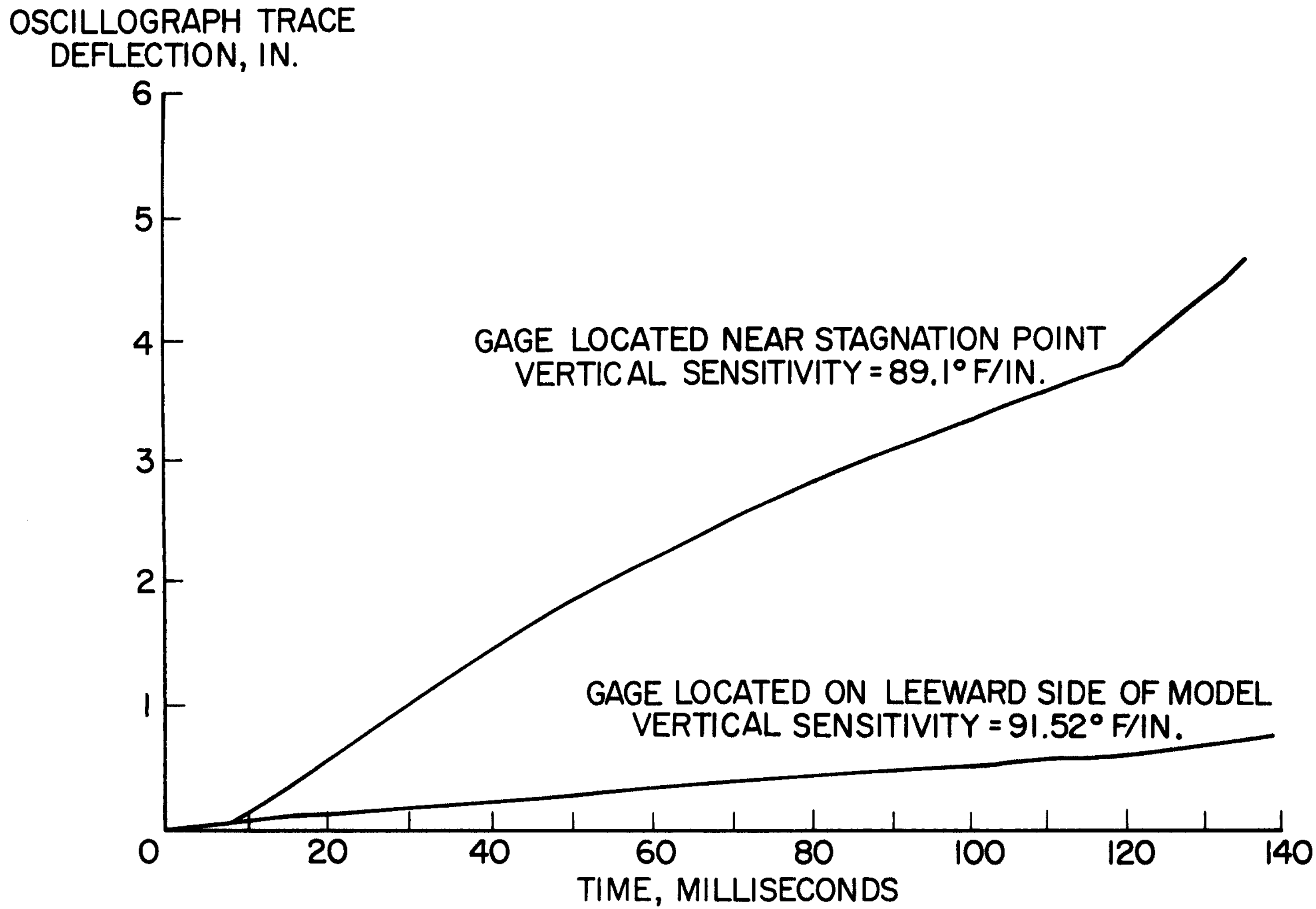

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Figure 10.- Typical data traces.

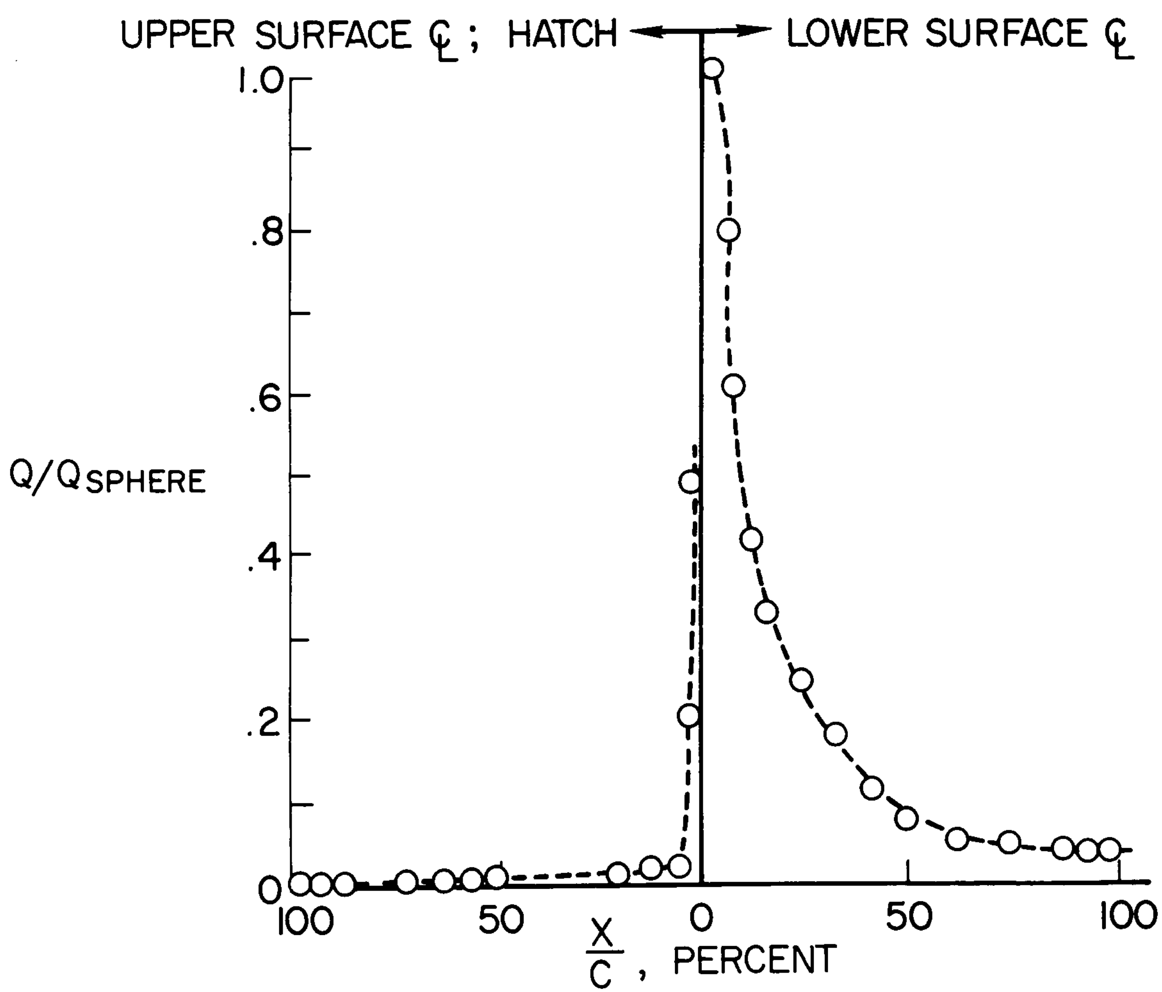

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Figure 11.- Representative heating-rate distribution for reentry configuration.

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