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TECHNICAL MEMORANDUM
X - 34

ELEVATED-TEMPERATURE TESTS UNDER STATIC AND AERODYNAMIC CONDITIONS ON CORRUGATED-STIFFENED PANELS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON September 1959

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ELEVATED-TEMPERATURE TESTS UNDER STATIC AND AERODYNAMIC CONDITIONS ON CORRUGATED-STIFFENED PANELS*

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SUMMARY

Thermal-insulating panels made of 0.005-inch-thick corrugated-stiffened sheets of Inconel X, backed by either bulk or reflective insulation, were tested under static and aerodynamic conditions at elevated temperatures up to 1,800° F in front of a quartz-tube radiant heater and in a blowdown wind tunnel at a Mach number of 1.4. The tests were performed to provide information on the structural integrity and insulating effectiveness of thermal-insulating panels under the effects of aerodynamic heating.

Static radiant-heating tests showed that the bulk insulation protected a load-carrying structure better than did the reflective insulation; however, the bulk insulation was much heavier than the reflective insulation and made the panel assemblies about three times as thick. Three of the four panels tested in the heated supersonic wind tunnel fluttered and failed dynamically. However, one panel demonstrated that flutter can be alleviated considerably with proper edge support. The panels deflected toward the heater (or into the airstream) at a rate which was primarily dependent on the temperature difference through the panel thickness.

INTRODUCTION

The effects of aerodynamic heating on the load-carrying components of an airframe during high-speed flight constitute a major structural design problem. These effects can be divided into two groups: (1) those, resulting from a temperature rise, which cause alteration of the mechanical properties in the heated materials, and (2) those, resulting from a nonuniform temperature distribution, which cause unequal thermal expansions which, in turn, can cause thermal stresses.

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*Title, Unclassified.

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One way to counteract these effects is to protect the load-carrying structure from aerodynamic heating with a lightweight thermal insulation. Some examples of this type of construction are discussed in reference 1 which shows that for short-term high-speed flights, insulation alone can furnish adequate protection. For flights of longer duration, wherein an internal cooling system is employed, insulation serves to reduce the cooling capacity required.

The present investigation was made in order to provide information on the structural integrity and insulating effectiveness of a corrugated-stiffened insulating panel under the effects of aerodynamic heating. The results are, therefore, presented for tests on eleven corrugated-stiffened panel assemblies at elevated temperatures. The panel assemblies used in the investigation were fabricated and supplied by Bell Aircraft Corporation from proprietary designs and were tested both by static radiant heating and in a supersonic blowdown wind tunnel. The static tests were made in the Langley Structures Research Division, and the aerodynamic tests were performed at the NASA Wallops Station.

A short discussion of the results of these same tests is given, without data, in reference 2; however, a more complete description of the insulating panels and an amplification of the results are presented herein.

PANEL ASSEMBLIES AND TEST EQUIPMENT

Panel Assemblies

Each panel assembly consisted of a corrugated-stiffened panel, insulation, a backplate, hat-type supports, and retainer straps. (See figure 1.)

Corrugated-stiffened panels.- The corrugated-stiffened panels, referred to hereinafter simply as panels, were composed of a skin stiffened on one surface by a corrugated sheet. The skin was a 0.005-inch-thick-flat Inconel X sheet approximately 8 inches wide by 12 inches long. Two expansion joints formed by V-type creases in the skin divided the surface into three sections. The corrugated sheet was made of 0.005-inch-thick Inconel X with a 0.312-inch pitch and amplitude. The skin and corrugated sheet were joined by seam welding. Detail 1 in figure 1(a) shows a cross-sectional view of a typical panel.

Insulation.- The panels were backed by one of two types of insulation: (1) a bulk insulation 0.94 inch thick, or (2) a reflective insulation which was a thin flat sheet of polished aluminum foil. The

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panels backed by bulk insulation are shown in figure 1(a), and the panels backed by reflective insulation are shown in figure 1(b).

Backplate and panel supports.- The panel and the insulation were placed in front of a 0.25-inch-thick steel backplate which was used to simulate a load-carrying structure. The panels backed by bulk insulation were held away from the backplate by hat-type supports in order to provide room for the insulation. (See detail 2 in figure 1(a).) These supports were designed as nonrigid members so that thermal expansion of the panel would not be hindered, were formed of 0.020-inch-thick stainless steel, and were riveted to the backplate. On some panels a 0.062-inch-diameter wire was inserted between the top of the hat-type supports and the bottom of the corrugation to insure that the panels would be firmly supported yet free to expand with little frictional resistance during heating.

The panels backed by reflective insulation also utilized a clearance between the bottom of the corrugations and the backplate to provide room for the polished aluminum foil. (See detail 2 in figure 1(b).) This clearance was provided by inserting 0.062-inch-diameter wires between the panel and the backplate; these wires, in turn, allowed the panel to expand with little frictional resistance during heating.

Frame and retainer straps.- The panel, insulation, and backplate were enclosed in a structural steel frame. The bottom of the frame was then bolted to the backplate. The top of the frame and a strip approximately 0.19 inch wide around the periphery of the skin of the panel were covered with retainer straps.

Edge Conditions

The panel assemblies, described previously, differed according to skin edge conditions and also according to the type of insulation (bulk or reflective). The skin edge conditions were of four variations, numbered and described as follows:

(1) Straight edge. All four edges of the skin were cut off in a straight line. (See fig. 1(c).)

(2) V-notched edge. V-type notches in the shape of isosceles triangles with 0.12-inch altitudes and 0.20-inch bases were cut in the side skins between seam welds. (See fig. 1(d).)

(3) Rounded notches. Rounded notches, approximately 0.20 inch wide by 0.12 inch deep, were ground in the skin between seam welds. (See fig. 1(e).) Also, the leading and trailing edges of the skin were notched at two locations (2 inches from each edge) with semicircular cutouts of

0.06 inch radius, the retainer straps were chamfered where they came in contact with the panel skin at the leading and trailing edges, and a dry lubricant (powder) was rubbed between the retainer straps and the panel skin. In addition, the expansion joints were slit, except in the vicinity of the instrumentation, during the static radiant-heating tests but were left intact during the aerodynamic tests.

(4) Brazed angle supports. All four skin edges were crimped as shown in figure 1(f). Along the two chordwise edges angles of 0.03-inch-thick material were brazed to one leg of the crimped skin and to the ends of the corrugations. Along the leading and trailing edges, a flat stiffener 0.25 inch wide and 0.03 inch thick was brazed to the extended leg of crimped skin.

Panel Designations

The eleven panel assemblies used in the investigation are hereinafter described by an alphabetical and numerical notation to designate the type of insulation used and the edge conditions. Insulation is signified by the letters B (bulk) or R (reflective). Edge conditions are designated by the numeral describing that particular modification which is appropriate, as indicated in the preceding section. For example, panel B-3 refers to a panel backed by bulk insulation with edge condition (3) as given in the preceding section titled "Edge Conditions."

Of the eleven panel assemblies used, seven (one B-1, one R-2, two B-3, two R-3, and one B-4) were tested in front of a static radiant heater and four (two B-3, one R-3, and one B-4) were tested in an elevated-temperature supersonic blowdown wind tunnel. Skin edge conditions (2) and (3) were on-the-spot modifications of condition (1) and were made during testing, while edge condition (4) was that of a completely redesigned panel.

Test Fixture

In order to perform aerodynamic tests at elevated temperatures, a fixture incorporating a radiant heater was designed to fit the nozzle exit of a blowdown wind tunnel. This test fixture was equally adaptable for static radiant-heating tests.

The fixture consisted of a Mach number 1.4, 12- by 12-inch nozzle block and an attached structural steel framework. The framework held a panel assembly, a movable radiant heater, and reflectors in position at the nozzle exit so that the panel assembly was virtually an extension of one of the nozzle side walls. A wedge-shaped leading edge on the framework scooped off a 0.125-inch boundary layer ahead of the panel assembly which was located 0.125 inch from the nozzle wall into the airstream.

A quartz-tube radiant heater was mounted on the framework just outside the airstream and opposite and parallel to the panel assembly. The radiant heater could be moved, to vary the distance between the panel assembly and the heater, by actuation of a hydraulically operated cylinder. Reflector plates were attached at the top and bottom of the nozzle to contain the radiant energy between the heater and the panel assembly. Photographs of the test apparatus (including the tunnel nozzle), the structural-steel framework, a panel assembly, reflectors, and radiant heater are shown in figure 2. A more complete description of the radiant heater is given in the appendix of reference 3.

Instrumentation

The instrumentation used during the investigation consisted of thermocouples, deflection-measuring devices, and high-speed motion-picture cameras.

Thermocouples.- Each panel was instrumented with 21 thermocouples of No. 30 chromel-alumel wire located as shown in figure 3, except that one of the B-3 panels had thermocouples positioned as shown in figure 4 and that two of the B-4 panels had only 7 thermocouples (thermocouples 5 to 10 and 16) located as shown in figure 3. Thermocouples were attached to the skin and to the corrugated sheet by spotwelding and were peened into small holes drilled into the backplate.

Deflectometers.- Some of the panels were fitted with deflectometers to measure out-of-plane deflections. A deflectometer consisted of a spring-steel cantilever beam, to which was fastened a push rod which, in turn, passed through a hole in the backplate and rested against a small metal pad spanning the distance between two adjacent corrugations. The push rod was held in position by a slight pressure from a coil spring. Displacement of the push rod produced a deflection of the beam. Changes in strain at the root of the cantilever were determined by four wire strain gages connected to form a four-active-arm Wheatstone bridge whose output was recorded on an oscillograph. Deflectometers, when used, were attached near the centers of the midstream and downstream sections of the panels.

Cameras.- Photographs were taken after most of the static radiant-heating tests. During the aerodynamic tests, a visual record of panel behavior was recorded by 16-millimeter motion-picture cameras operating at speeds of 85 or 1,000 pictures per second. All cameras were located

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to one side of the nozzle center line, and were directed upstream at an angle of approximately 45° from the panel assembly. Complete motion-picture coverage was obtained for the first two tunnel tests (when the heaters were not energized). Motion-picture coverage of subsequent tests was limited to that time during which the radiant heater was energized because of the large variation in lighting intensity.

Accuracy

Given in the following table are the estimated probable errors in individual measurements and the corresponding time constants. The time constant, which is considered independent of the probable error, is defined as the time at which the recorded value of a step function input is 63 percent of the input; at three time constants, the response amounts to 95 percent of the input. Errors due to thermocouple installation are not included, but are believed to be approximately ±2 percent according to data presented hereinafter.

Measurement of -	Probable error	Time constant, sec
Stagnation pressure	±0.4 psi	0.03
Stagnation temperature	±4° F	0.12
Panel temperature	±6° F	0.03
Panel deflection	±0.006 in.	0.02

STATIC RADIANT-HEATING TEST PROCEDURE

The panels were to be tested at a temperature level as near as possible to 1,600° F in a Mach 1.4 blowdown wind tunnel. The wind tunnel, however, had a stagnation temperature of 680° F and a test duration of approximately 20 seconds; therefore, it was necessary to provide additional heating. This additional heating was supplied by a quartz-tube radiant heater placed opposite the panels and just outside the airstream. However, the large heat input required to raise the panel surface to 1,600° F during a test was expected to cause initial skin temperature rise rates of the order of several hundred degrees Fahrenheit per second.

In order to observe panel behavior at high skin temperature rise rates without the effect of air flow, twenty preliminary static

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radiant-heating tests were performed on four panel assemblies. Subsequent to these preliminary tests, six additional static radiant-heating tests were made in order to evaluate panel insulating effectiveness and to measure panel deflections.

During each of the static radiant-heating tests, the fixture was mounted on a wall in the Langley Structures Research Division. The panel assemblies were positioned in the holding fixture opposite the radiant heater and were subjected to heating rates which were controlled by adjustment of the heater-to-panel distance and by variation of the voltage to the heater. The panel types tested, along with pertinent test conditions are given in table I.

RESULTS AND DISCUSSION OF STATIC RADIANT-HEATING TESTS

Panel Behavior

During the preliminary static radiant-heating tests (1 to 20) on panels B-1, R-2, B-3, and R-3, severe skin surface deformations of two distinct types, creases and rectangular buckles, were observed. These observations are given in table I(a).

Creases (similar in appearance to the V-type expansion joints, see figs. 5(a) and 5(b)) began to form in each of the three skin sections at temperatures of approximately 900° F. In all cases, the creases first appeared at the panel edges and grew parallel to the seam welds with increasing temperatures. As a result of the application of various stress-relief techniques in the form of skin edge conditions (2) and (3), and in particular condition (4), (see section titled "Edge Conditions") the creases were alleviated up to a temperature of 1,800° F.

Rectangular buckles, approximately 0.3 inch by 0.5 inch began to form on the surface of the skin at temperature differences through the panel thickness of approximately 600° F and at heating rates of 100° F per second. (See fig. 5(c).) The buckles first formed diagonally in the corners of the three skin sections and gradually spread and alined themselves with the panel edges. The rectangular buckles are attributed to compressive stresses in the skins caused by a temperature difference through the panel thickness, according to a theory presented in reference 4. The theory given in reference 4 was developed for plate structures in which opposite sides were symmetrically heated so as to produce only axial deformations. This theory does not apply in the present study since bending deformations caused by unsymmetrical heating took place; however, the relationship between permanent panel buckling and temperature difference through the panel thickness is similar to that of reference 4.

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Insulating Effectiveness

Measurements of the insulating effectiveness of three panels (B-3, R-3, and B-4) were made during tests 21 to 23 by subjecting each panel to a comparable heating cycle. The heating cycle was composed of an initial interval, during which the skin temperature was raised 20° F per second until 1,500° F was reached, and a second interval, during which a temperature of 1,500° F was maintained for 45 seconds. Temperature data are given in table II(a).

Temperature histories showing skin temperatures, corrugation temperatures, and backplate temperatures are plotted in figure 6. The temperatures, plotted at 10-second intervals, were obtained by averaging, separately, readings of all the skin thermocouples, the corrugation thermocouples, and the backplate thermocouples except those which were known to be seriously affected by retainer straps (thermocouples 6 and 7) or by expansion joints (thermocouples 18 and 19). (Thermocouple 1, test 22, gave widely divergent readings for no apparent reason and was arbitrarily discarded from the average.) In some cases the remaining skin temperatures differed from an average value by ±10 percent, and some of the backplate and corrugation temperatures differed from their respective averages by ±30 percent.

As an accuracy check, thermocouples were installed in duplicate for panel B-3, test 21. (See fig. 4.) The data show that for duplicated thermocouples the temperatures were essentially the same and agreed within ±2 percent. However, the temperature variation between groups of thermocouples over the surface of the panel showed that the temperature distribution was not uniform. (For instance, thermocouples 1 and 2 gave readings that were 7 percent lower than thermocouples 5 and 6.) This nonuniform temperature distribution is attributed to electrical unbalance among the three phases supplying current to the radiant heater.

Even though temperatures which vary widely have been used, the results presented in figure 6 illustrate the ability of the different panel types to retard the flow of heat into the backplate. For the present tests all the panel types protected the backplate reasonably well. Bulk insulation protected a load-carrying structure more than did reflective insulation; however, the bulk insulation was much heavier than the reflective insulation and made the panel assemblies about three times as thick. For the short-term (2-minute) tests, the B-panels with bulk insulation allowed a maximum backplate temperature rise of 15° F, while an R-panel with reflective insulation allowed a backplate temperature rise of 184° F.

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Deflections

Measurements of out-of-plane deflections on panels B-3, R-3, and B-4 were obtained by deflectometers during tests 21 to 26. Deflection data are given in table III, and plots of deflection histories are shown in figure 7. During tests 21 to 23, at a skin temperature rise rate of 20° F per second, all the panels deflected in a similar manner and moved toward the heater at a decreasing rate. An average value of approximately 0.056 inch was reached at the end of 40 seconds. Additional tests (24 to 26) on panel B-4 were made to determine deflection sensitivity with regard to the front surface temperature rise rate. Values showing an average trend for deflections are given in the following table which was obtained from plots in figure 7(d) and the data in table II(a).

Test	Panel	Front surface temperature rise rate, °F/sec	Maximum temperature difference through panel thickness, °F	Heating rate, Btu/sq ft-sec	Maximum deflection, in.	Time at which maximum deflection was reached, sec
23	B-4	20	217	0.6	0.056	40
24	B-4	10	124	.3	.030	70
25	B-4	40	333	1.2	.100	28
26	B-4	80	531	2.4	.152	16

The plot in figure 7(d) for a skin temperature rise rate of 40° F per second shows that panel deflection was reduced after a peak value was reached. This behavior can be explained through analysis of a thermally loaded flat plate which shows that deflection is dependent on the temperature difference through the plate thickness. This temperature difference, in turn, is dependent on the heating rate and the interval of heating. For static radiant-heating tests 23 to 26 on panel B-4, an empirical relationship was determined by drawing a straight line through a plot of panel deflections against average temperature differences through the panel thickness. The panel deflection was found to be proportional to 0.00028 times the temperature difference, and a correlation with experimental data is shown in figure 7(d).

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WIND-TUNNEL TEST PROCEDURE

The aerodynamic tests were made in the preflight jet of the NASA Wallops Station used as a Mach 1.4 blowdown wind tunnel. The tunnel was operated by opening a pressure control valve which allowed dry air to escape from two storage spheres and pass through a heat accumulator before entering a 12- by 12-inch Mach 1.4 nozzle. The panels were tested in a free stream at the exit of the nozzle.

Data for the aerodynamic tests are shown in table IV. The values given for stagnation pressure were averaged from measurements taken at selected points in the cross section of the airstream. The stagnation temperature was obtained in the same manner but, in addition, was corrected for the position of the test panels in the airstream according to the results of profile surveys made on the nozzle used in these tests. Values obtained in this way are approximate but provide a reasonable estimate of the true stagnation temperature. Other tunnel conditions were computed from these stagnation-pressure and temperature values.

In order to perform aerodynamic tests at panel skin temperatures as near to 1,600° F as possible, the radiant heater in the fixture was energized during three of the five aerodynamic tests. The use of this device allowed testing, during blowdown, at panel skin temperatures in excess of the tunnel stagnation temperature. The panels tested, the skin temperature reached during blowdown, and pertinent details are given in table I(c).

RESULTS AND DISCUSSION OF WIND-TUNNEL TESTS

Five aerodynamic tests were made on four panel assemblies. Two configurations (B-3 and R-3) were tested both with and without additional radiant heating. Panel B-4 was subjected to a combination test in which the tunnel ran for 11 seconds before the radiant heater was energized.

A motion-picture film supplement has been prepared and is available on loan. A request card form and a description of the film will be found at the back of this paper on the page immediately preceding the abstract and index pages.

Temperatures and Insulating Effectiveness

Recorded temperatures for the aerodynamic tests are given in table II(b). Graphs of representative tests show skin temperatures,

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corrugation temperatures, and backplate temperatures plotted against time in figure 8. The plotted temperatures were obtained by averaging, separately, readings of all the skin thermocouples, the corrugation thermocouples, and the backplate thermocouples except those which were known to be seriously affected by retainer straps (thermocouples 6 and 7) or by expansion joints (thermocouples 18 and 19). In some cases the remaining skin temperatures differed from an average value by ±15 percent, and the backplate and corrugation temperatures differed from their respective averages by ±25 percent.

The tunnel tests provided little information on the insulating effectiveness of the various panels because of the brevity of the tests. In general, the temperature rise in the backplate was approximately proportional to that experienced during the static radiant-heating tests.

Panel Behavior

Flutter.- The two B-3 panels fluttered and failed during tests, both with and without additional radiant heating. The R-3 panel survived the test without radiant heating but fluttered and failed at temperatures under 800° F when radiant heating was added. The B-4 panel survived an aerodynamic test with temperatures up to 968° F during air flow with only a slight indication of vibration of small amplitude. These results demonstrated the importance of edge-support conditions.

All of the panels which fluttered did so in a similar manner distorting into long buckles which were about 1 inch wide and parallel to the corrugations. These buckles gave the panel what might be described as a washboard surface. A motion-picture camera speed of 1,000 pictures per second was insufficient to establish the exact details of the motion; however, the flutter mode is shown in the film supplement which is available on loan. (Ref. 5 discusses tests at higher Mach numbers on similar panels in which strain-gage records showed frequencies of 580 cycles per second.)

Deflections.- Deflectometers were used during the tunnel tests to record panel deflections. The data obtained are shown in table III. The panel deflections were approximately 25 percent larger than those obtained for comparable temperature differences through the panel thickness during the static radiant-heating tests, and this condition indicated an increase in the constant of proportionality between deflection and temperature difference through the panel thickness. This increase in deflection is attributed to panel vibration during the tunnel tests which reduced the edge restraint of the clamped angle supports.

Skin deformations.- Of the two panels (R-3 and B-4) which survived the aerodynamic tests, panel R-3, test 28, did not exhibit skin deformations since the skin temperature rise rates, the temperature levels, and the temperature differences through the panel thickness were below the values at which deformations had been previously noted to occur. Panel B-4, test 30, showed that creasing can be controlled by proper edge-support design. Also, this panel exhibited small rectangular buckles similar to those observed during the static radiant-heating tests. (See fig. 5(c).) The small rectangular buckles observed in these tests as well as in the static radiant-heating tests, are attributed to thermal compressive stresses caused by a temperature difference of sufficient magnitude through the panel thickness.

CONCLUDING REMARKS

Corrugated-stiffened panels were tested at elevated temperatures under both static and aerodynamic conditions. The panels differed in type of insulation, in skin edge conditions, and in support details. For some of the aerodynamic tests a radiant heater was used, in addition to the heat accumulator of the tunnel, to increase the skin temperature of the panel above the tunnel stagnation temperature.

Tests during a heating cycle composed of an initial interval in which the exposed surface was heated at 20° F per second until 1,500° F was reached and a second interval of 45 seconds wherein a temperature of 1,500° F was maintained showed that the panels backed by a bulk insulation protected a load-carrying structure more than did a reflective insulation; however, the bulk insulation was much heavier than the reflective insulation and made the panel assemblies about three times as thick. For short-term (2-minute) tests, the reflective insulation allowed a 184° F temperature rise in the protected portion of a panel assembly while the bulk insulation allowed only a 15° F temperature rise.

The panels deflected toward the heater (or into the airstream), at a rate which was dependent on the temperature difference through the panel thickness.

High heating rates and large temperature differences through the panel thickness produced local skin surface deformations. Creases of variable length and depth occurred parallel to the corrugations. The number, length, and depth of the creases were reduced by modifications to the skin edges. In one case involving a redesigned edge support, these creases were eliminated up to temperatures of 1,800° F. Small rectangular buckles became pronounced over the surface of all panels at skin temperature rise rates of approximately 100° F per second and temperature differences through the panel thickness of approximately 600° F.

Three of the four panels tested under aerodynamic conditions fluttered and failed dynamically. However, one panel with a redesigned edge support survived a Mach 1.4 test at a temperature maximum during air flow of 968° F. The improved performance of this surviving panel is attributed to the increased rigidity of the panel edge support.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Field, Va., April 6, 1959.

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TABLE I.- TEST CONDITIONS AND OBSERVATIONS

(a) Preliminary static radiant-heating tests on four panels

Test	Panel	Maximum skin temperature, °F	Maximum temperature difference through panel thickness, °F	Skin temperature rise rate, °F/sec	Observations
1	B-1	900	340	55	Faint creases
2		1,600	300	35	Creases more pronounced
3		1,700	650	140	Number of creases increased
4		1,700	850	240	Faint rectangular buckles
5		2,000	1,070	390	Pronounced rectangular buckles
6	R-2	1,300	375	55	Faint creases
7		1,580	600	75	Faint creases
8		1,780	790	150	Pronounced creases and faint rectangular buckles in corners
9		1,875	1,000	270	Pronounced creases and faint rectangular buckles in corners
10		1,900	1,200	425	Creases and more pronounced rectangular buckles
11	B-3	1,675	600	100	Creases
12		1,640	685	112	Creases and faint rectangular buckles
13		1,655	820	200	Creases and more pronounced rectangular buckles
14	R-3	1,000	140	7	Faint creases
15		1,100	200	23	Faint creases
16		1,100	345	50	Faint creases
17		1,100	595	100	Faint rectangular buckles
18		1,700	200	9	Creases and faint rectangular buckles
19		1,700	275	30	Creases and rectangular buckles
20		1,700	755	220	Creases and more pronounced rectangular buckles

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TABLE I.- TEST CONDITIONS AND OBSERVATIONS - Concluded

(b) Static radiant-heating tests

Test	Panel	Skin-temperature rise rate, °F/sec	Purpose
21	B-3	20° F/sec to 1,500° F, and 1,500° F for 45 additional seconds	Measurement of temperatures and deflections
22	R-3	20° F/sec to 1,500° F, and 1,500° F for 45 additional seconds	Measurement of temperatures and deflections
23	B-4	20° F/sec to 1,500° F, and 1,500° F for 45 additional seconds	Measurement of temperatures and deflections
24		10	Measurement of temperatures and deflections
25		40	Measurement of temperatures and deflections
26		80	Measurement of temperatures and deflections

(c) Wind-tunnel tests

Tests	Panel	Additional radiant heating, sec		Maximum temperature of panel skin during blowdown, °F	Stagnation temperature, °F	Test duration, sec	
		On	Off			Jet air off	Panel failure (approx.)
27	B-3	None	None	288	620	23	2
28	R-3	None	None	400	644	29	No failure
29	R-3	2.02	16.02	759	661	30	14
30	B-4	10.96	29.96	968	683	24	No failure
31	B-3	11.01	30.01	610	675	44	32

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TABLE II.- TEMPERATURE DATA

(a) Static radiant-heating tests

Test	Panel	Time, sec[c]	Temperature at thermocouple, °F																				
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
21	B-3	0	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	78	(b)
		10	289	285	301	299	311	297	278	145	131	143	137	161	273	144	79	78	78	78	79	78	
		20	452	442	423	470	484	464	441	201	212	282	262	303	438	286	80	78	78	78	79	78	
		30	642	634	681	677	693	674	634	270	295	449	418	371	619	457	86	84	79	79	79	78	
		40	839	828	880	877	891	877	834	353	395	652	613	499	815	667	92	90	80	79	80	79	
		50	1,051	1,037	1,090	1,085	1,101	1,098	1,050	460	520	868	829	635	1,020	893	101	98	79	78	80	79	
		60	1,245	1,232	1,278	1,282	1,286	1,304	1,248	593	682	1,085	1,060	782	1,218	1,122	119	116	80	78	81	79	
		70	1,430	1,418	1,460	1,466	1,467	1,496	1,446	752	874	1,292	1,277	941	1,411	1,344	150	148	80	78	82	79	
		80	1,472	1,466	1,499	1,509	1,511	1,548	1,519	839	989	1,402	1,398	1,037	1,478	1,466	194	197	83	79	84	80	
		90	1,466	1,463	1,493	1,502	1,507	1,544	1,521	881	1,013	1,415	1,416	1,077	1,481	1,485	245	252	84	79	87	80	
		100	1,477	1,474	1,504	1,511	1,517	1,557	1,536	924	1,042	1,433	1,435	1,120	1,496	1,504	296	307	86	79	90	81	
		110	1,471	1,468	1,499	1,502	1,510	1,548	1,533	958	1,066	1,439	1,443	1,150	1,493	1,510	345	360	88	81	93	83	
		120	1,395	1,397	1,419	1,425	1,432	1,464	1,480	967	1,070	1,426	1,429	1,163	1,449	1,496	392	414	89	81	96	84	
22	R-3	0	80	80	80	80	80	80	80	(b)	80	80	80	80	80	80	80	80	(d)	80	80	80	80
		10	197	261	81	81	81	158	181		127	254	121	254	249	124	265	226		121	223	276	273
		20	308	435	84	82	82	239	273		249	430	236	414	412	217	435	377		225	377	465	457
		30	434	638	88	85	83	326	368		410	636	400	599	590	336	623	553		382	558	676	674
		40	567	853	97	90	86	417	468		599	839	592	781	765	471	813	735		525	740	903	882
		50	720	1,107	111	99	91	530	598		799	1,072	794	1,014	974	622	1,055	963		710	951	1,162	1,132
		60	839	1,302	131	110	97	641	717		976	1,236	981	1,227	1,160	791	1,241	1,160		890	1,130	1,346	1,319
		70	959	1,510	153	124	105	793	884		1,161	1,426	1,169	1,454	1,407	993	1,477	1,388		1,097	1,339	1,566	1,515
		80	982	1,548	182	143	118	936	1,021		1,256	1,468	1,260	1,486	1,464	1,155	1,517	1,480		1,253	1,432	1,602	1,547
		90	979	1,536	204	160	130	1,014	1,096		1,265	1,465	1,267	1,467	1,452	1,191	1,508	1,480		1,274	1,431	1,587	1,542
		100	982	1,536	225	181	144	1,054	1,146		1,275	1,471	1,280	1,460	1,499	1,208	1,500	1,469		1,277	1,434	1,586	1,542
		110	986	1,537	246	200	159	1,081	1,172		1,286	1,479	1,303	1,458	1,451	1,226	1,498	1,464		1,301	1,459	1,590	1,550
		120	983	1,530	265	216	172	1,099	1,192		1,308	1,486	1,324	1,463	1,457	1,239	1,492	1,464		1,317	1,478	1,588	1,548
23	B-4[a]	0					79	79	79		79	79						79					
		10					79	213	206	(b)	137	275						276					
		20					79	324	310		269	447						444					
		30					80	468	445		454	669						654					
		40					79	608	578		649	879						852					
		50					79	773	737		861	1,090						1,060					
		60					80	968	925		1,085	1,297						1,270					
		70					80	1,177	1,127		1,300	1,495						1,481					
		80					82	1,261	1,215		1,422	1,540						1,529					
		90					81	1,277	1,238		1,443	1,519						1,516					
		100					82	1,282	1,241		1,426	1,506						1,507					
		110					83	1,294	1,263		1,431	1,507						1,511					
		120					84	1,311	1,283		1,442	1,517						1,519					

[a] Panel B-4 was instrumented with only seven thermocouples.
[b] Indicates control thermocouple.
[c] Temperatures given for time 0 seconds are room temperatures.
[d] Thermocouple 17, test 22 was inoperative.

[redacted]

[redacted]

TABLE II.- TEMPERATURE DATA - Continued

(a) Static radiant-heating tests - Concluded

Test	Panel[a]	Time, sec[c]	Temperature at thermocouple, °F																				
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
24	B-4	0					80	80	80		80	80						80					
		15					80	196	185	(b)	156	238						237					
		30					81	284	266		273	381						369					
		45					80	375	351		407	534						512					
		60					81	465	434		545	683						646					
		75					81	573	536		692	838						795					
		90					84	695	648		855	1,000						956					
		105					82	831	777		1,029	1,149						1,117					
		120					85	1,023	964		1,190	1,303						1,286					
		135					85	1,215	1,155		1,334	1,445						1,445					
		140					86	1,285	1,227		1,383	1,500						1,507					
25	B-4	0					79	79	79		79	79						79					
		4					80	239	217	(b)	94	280						284					
		8					80	322	294		163	396						396					
		12					80	401	367		255	517						514					
		16					80	512	466		363	674						668					
		20					80	614	564		499	823						811					
		24					80	738	681		647	988						972					
		28					80	889	823		823	1,169						1,153					
		32					81	1,001	936		1,001	1,305						1,288					
		36					81	1,115	1,045		1,154	1,424						1,406					
		38					80	1,171	1,098		1,220	1,481						1,459					
26	B-4	0					80	80	80		80	80						80					
		2					78	194	168	(b)	80	239						247					
		4					79	344	300		99	427						429					
		6					79	460	410		157	583						585					
		8					78	556	498		247	720						718					
		10					79	653	590		360	858						852					
		12					80	768	695		486	1,009						997					
		14					79	890	810		632	1,160						1,153					
		16					80	1,040	954		805	1,337						1,334					
		17.5					79	1,162	1,071		952	1,478						1,476					

[a] Panel B-4 was instrumented with only seven thermocouples.
[b] Indicates control thermocouple.
[c] Temperatures given for time 0 seconds are room temperatures.

[redacted]

[redacted]

TABLE II.- TEMPERATURE DATA[a] - Concluded

(b) Wind-tunnel tests

Test	Panel	Time, sec	Temperature at thermocouple, °F																				
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
27	B-3	0	118	123	86	90	85	100	98	112	101	112	101	104	105	96	106	108	98	95		103	107
		1	176	170	84	148	84	223	196	204	110	184	112	166	179	119	170	192	108	196		151	204
		2	220	216	85	136	85	238	192			242	124	184	222	134	200	256	128	288			
28	R-3	0	116	121	88	90	88	95	96	104	92	110	94	107	105	91	109	108	92	92	96	111	106
		3	278	274	89	204	110	233	240	222	105	253	110	259	274	124	258	291	117	350	361	282	285
		6	316	310	92	240	129	265	280	270	142	293	144	318	313	174	318	341	168	351	380	329	332
		9	334	328	94	269	140	253	280	288	166	305	160	326	328		327	353	201	303	332	343	348
		12	348	341	96	286	150	272	302	306	192	321	182	340	345		341	369	228	280	325	355	362
		15	358	351	100	301	158	280	310	318	210	330	196	349	356		349	377	242	265	320	361	370
		18	364	358	102	320	164	306	331	326	222	340	207	362	366		363	384		280	308	368	376
		21	370	362	104	330	171	314	328	334	234	344	210	366	372		368	390		278	306	374	382
		24	374	368	105	342	178	328	326	336	244	352	220	376			376	395		332	352	380	386
		27	379	372	109	348	184	319	335	334	254	358	232	382			382	400		347	364	384	390
29	R-3	0	118	122	94	94	90	96	97	102	96	114	98	109	106	94	104	110	96	90	92	108	108
		3	324	339	94	166	116	134	164	174	120	294	106	278	307	128	282	328	129	173	163	353	
		6	639		98	249	138	212	270	365	188	689	184	613	657	236	608	716	252	258	252		
		9	710		102	299	154	252	319	481	310	792		606	743		680	801	391	295	264		
		12	759		110	338	176	336	369		269			583	518		567	650		415			
30	B-4[b]	0					92	104	104		100	114						102					
		3					92	318	304		113	315						268					
		6					90	347	338		145	346						313					
		9					92	369	366		178	366						340					
		12					91	502	483		206	534						451					
		15					94	764	726		266	864						651					
		18					92	844	802		384	934						753					
		21					92	892	852		486	968						829					
		24					93	1,015	962		584	1,126						954					
		27					96	1,424	1,373		832	1,608						1,369					
		30					95	1,604	1,568		1,198	1,804						1,638					
31	B-3	0	108		88	87	82			108				93	90					88	89		
		5	356		112	216	100			168				173	161					174	199		
		10	407		106	270	118			212				232	234						288		
		15	443		110	336	140			278				261	257						375		
		20	402		128	392	168			452				380	390						464		
		25	474		140	460	189			610				472	492						574		
		30	490			505				552				568	530						496		

[a]Blanks in data indicate thermocouple malfunction.
[b]Panel B-4 was instrumented with only 7 thermocouples.

[redacted]

[redacted]

TABLE III.- DEFLECTION DATA[a]

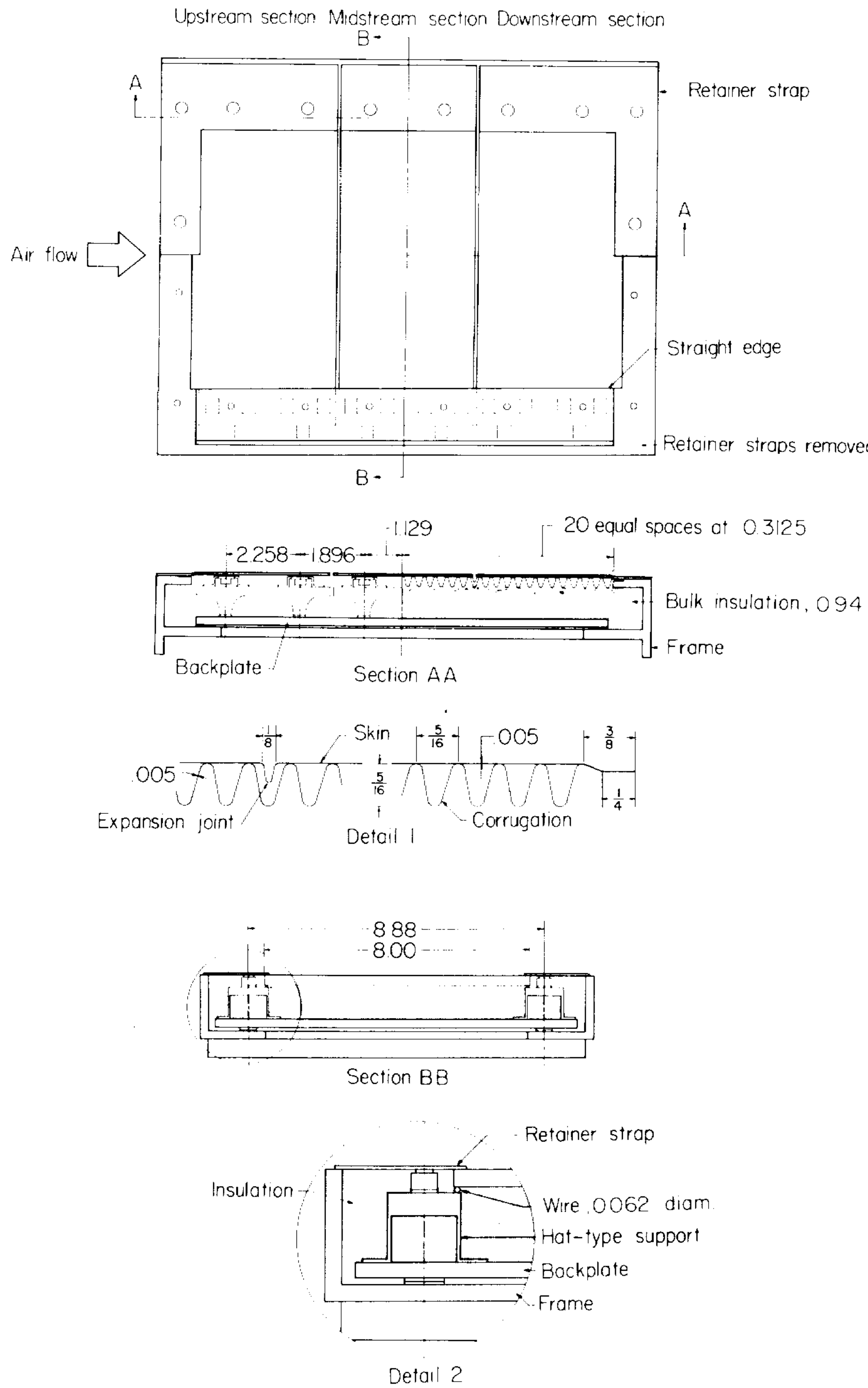
	Deflection, in.																				
Test	21		22		23		24			25			26			28			29		30
Panel	B-3		R-3		B-4		B-4			B-4			B-4			R-3			R-3		B-4
Time, sec	Mid-stream panel	Down-stream panel	Mid-stream panel	Down-stream panel	Mid-stream panel	Down-stream panel	Time, sec	Mid-stream panel	Down stream panel	Time, sec	Mid-stream panel	Down-stream panel	Time, sec	Mid-stream panel	Down stream panel	Time, sec	Mid-stream panel	Down-stream panel	Mid-stream panel	Down-stream panel	Mid-stream panel
0	0.000	0.000	0.000	0.000	0.000	0.000	0	0.000	0.000	0	0.000	0.000	0	0.000	0.000	0	0.000	0.000	0.000	0.000	0.000
10	+.038	+.034	+.031	+.032	+.036	+.031	15	+.018	+.022	4	+.050	+.058	2	+.052	+.056	3	+.025	+.054	+.070	+.081	+.063
20	+.052	+.045	+.047	+.047	+.046	+.041	30	+.022	+.027	8	+.057	+.067	4	+.088	+.100	6	+.043	+.034	+.139	+.148	+.067
30	+.064	+.056	+.057	+.055	+.054	+.051	45	+.026	+.030	12	+.066	+.076	6	+.108	+.123	9	+.037	+.026	+.129	+.122	+.061
40	+.064	+.058	+.057	+.054	+.056	+.054	60	+.027	+.030	16	+.077	+.089	8	+.119	+.133	12	+.038	+.025			+.119
50	+.065	+.062	+.062	+.060	+.057	+.055	75	+.028	+.032	20	+.080	+.090	10	+.126	+.140	15	+.036	+.023			+.166
60	+.064	+.062	+.058	+.055	+.057	+.055	90	+.026	+.032	24	+.088	+.095	12	+.133	+.147	18	+.034	+.019			+.155
70	+.058	+.062	+.074	+.072	+.056	+.054	105	+.027	+.031	28	+.092	+.108	14	+.140	+.150	21	+.034	+.020			+.139
80	+.036	+.045	+.057	+.050	+.032	+.024	120	+.029	+.034	32	+.088	+.089	16	+.148	+.156	24	+.032	+.018			+.155
90	+.028	+.038	+.052	+.044	+.016	+.008	135	+.028	+.032	36	+.080	+.078	17.5	+.150	+.154	27	+.030	+.017			+.206
100	+.027	+.038	+.052	+.046	+.020	+.010	140	+.032	+.037	38	+.080	+.076				30					+.157
110	+.030	+.034	+.052	+.046	+.023	+.018															
120	-.005	+.010	+.050	+.046	+.036	+.045															

[a]Plus signs indicate panel deflection toward the radiant heater or into the jet stream. The midstream and downstream deflectometers for tests 27 and 31, and the downstream deflectometer for test 30 were inoperative.

[redacted]

TABLE IV.- AERODYNAMIC TEST DATA

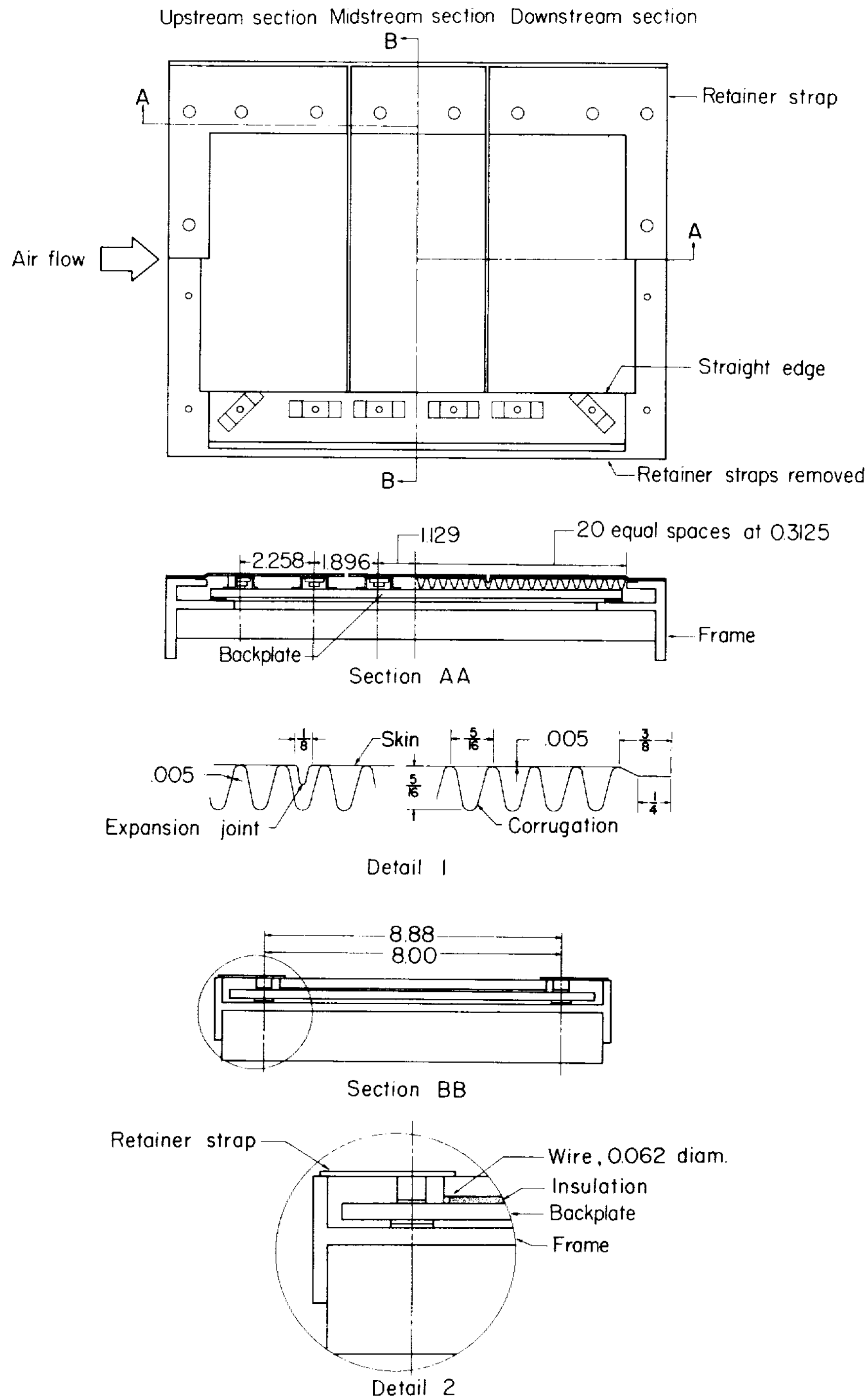
Test	Panel	Mach number	Stagnation temperature, °F	Stagnation pressure, lb/sq in. abs	Free-stream pressure, lb/sq in. abs	Free-stream dynamic pressure, lb/sq in. abs	Free-stream temperature, °F	Free-stream velocity, fps	Free-stream density, slugs/cu ft	Speed of sound, fps	Reynolds number per ft $\times 10^{-6}$	Time of radiant heating	
												On, sec	Off, sec
27	B-3	1.42	620	50.4	15.40	21.73	310	1,931	0.00168	1,360	6.48	None	None
28	R-3	1.42	644	49.6	15.15	21.38	327	1,952	.00162	1,375	6.22	None	None
29	R-3	1.42	661	50.3	15.37	21.69	339	1,968	.00161	1,386	6.16	2.02	16.02
30	B-4	1.42	683	50.1	15.30	21.57	354	1,985	.00158	1,398	6.02	10.96	29.96
31	B-3	1.42	675	49.9	15.24	21.50	349	1,979	.00158	1,394	6.02	11.01	30.01



(a) Panel with bulk insulation.

Figure 1.- Details of panel assemblies. Linear dimensions are in inches.

[redacted]

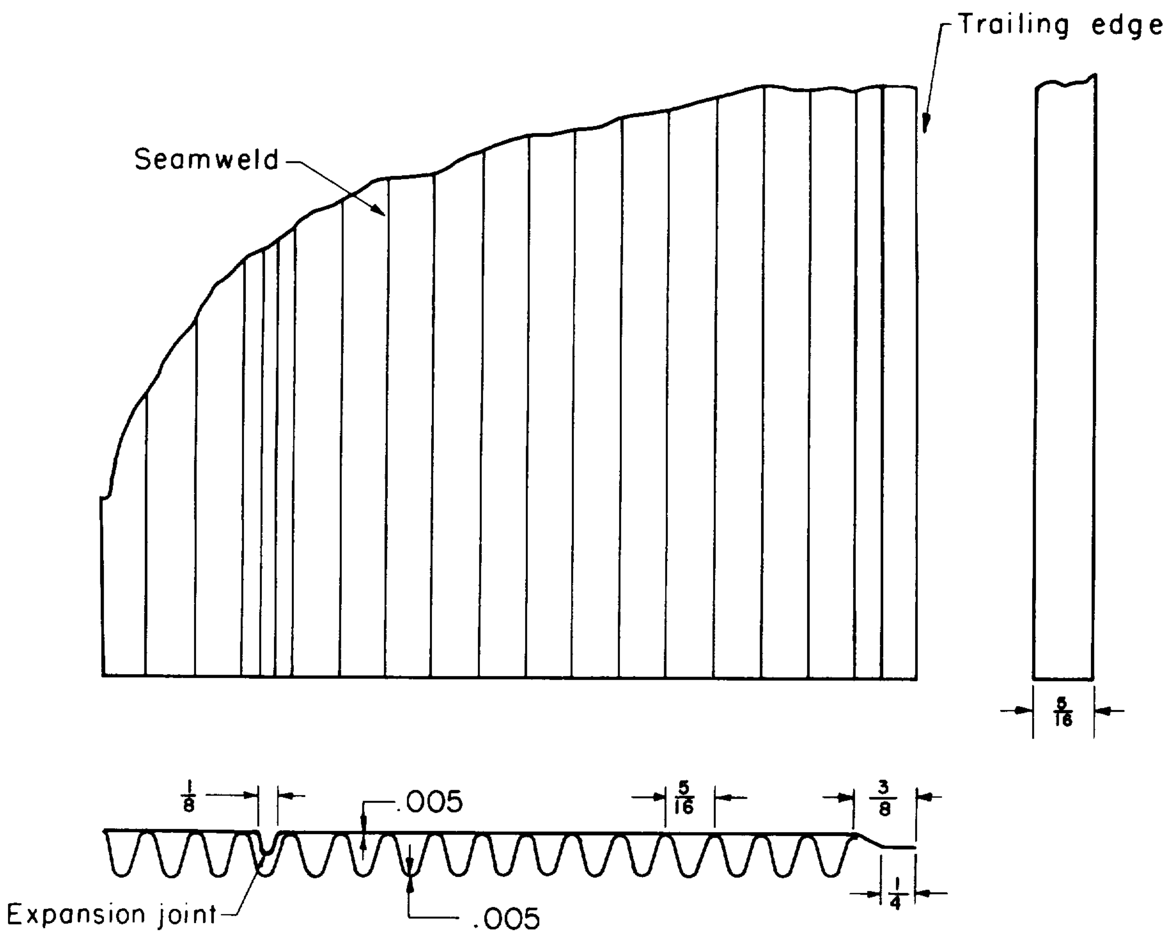


(b) Panel with reflective insulation.

Figure 1.- Continued.

[redacted]

[redacted]

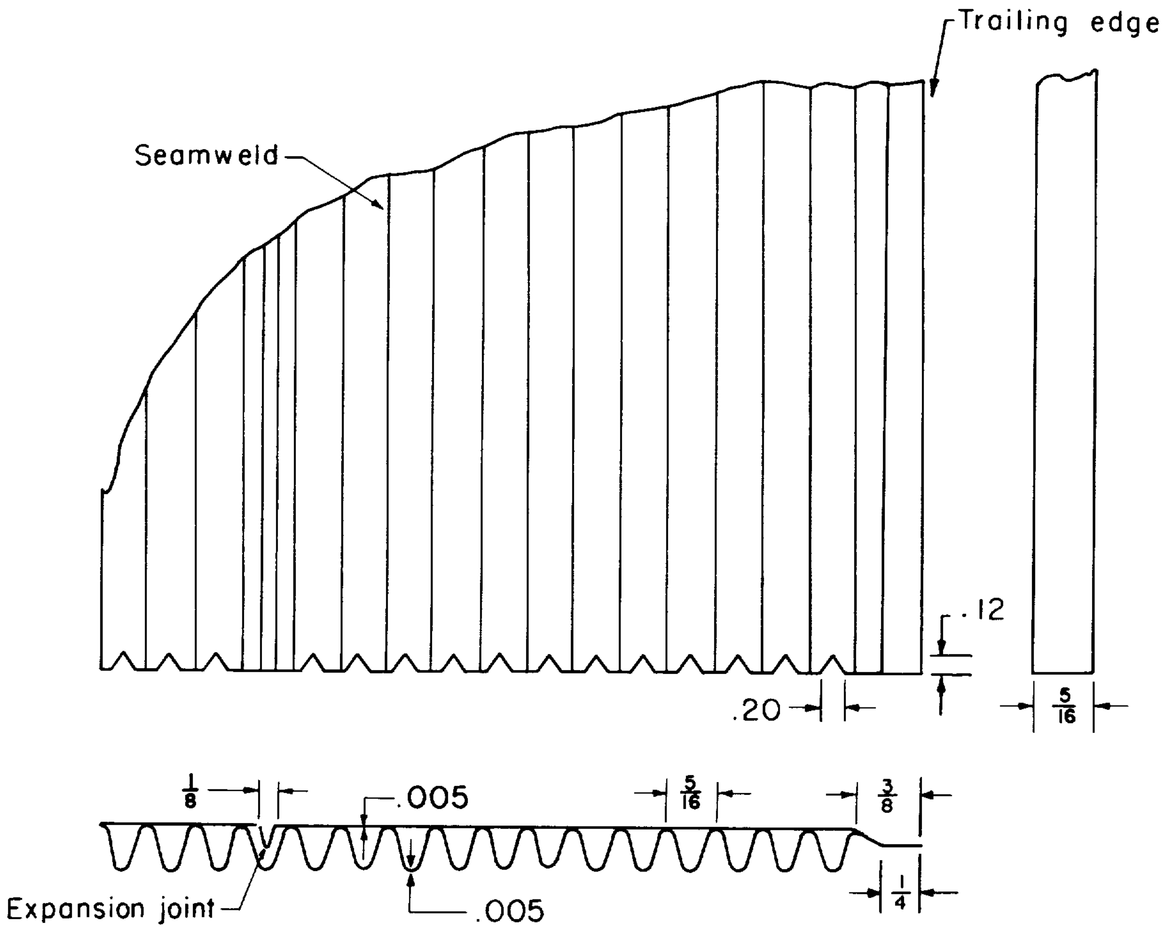


(c) Panel edge condition (1), straight edge.

Figure 1.- Continued.

[redacted]

[redacted]

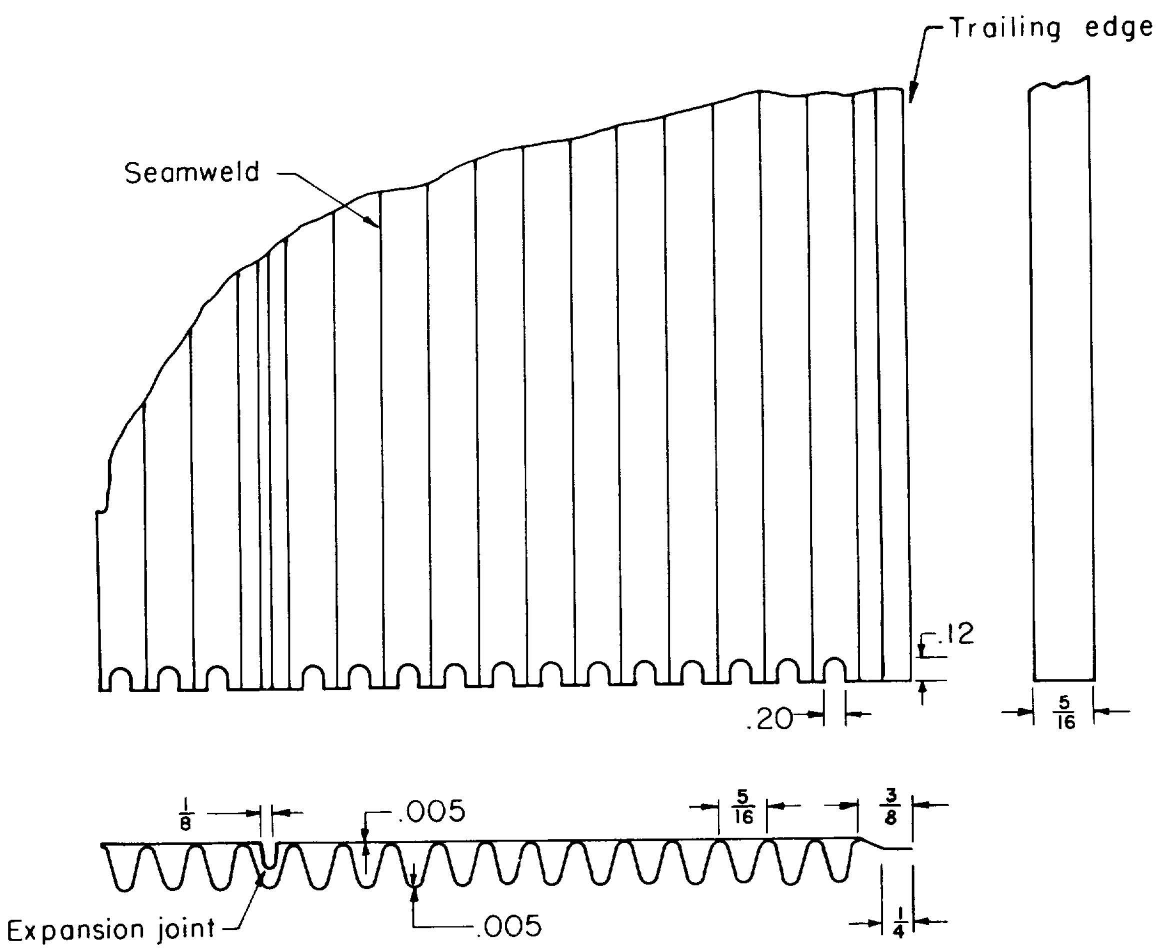


(d) Panel edge condition (2), V-type notches.

Figure 1.- Continued.

[redacted]

[redacted]

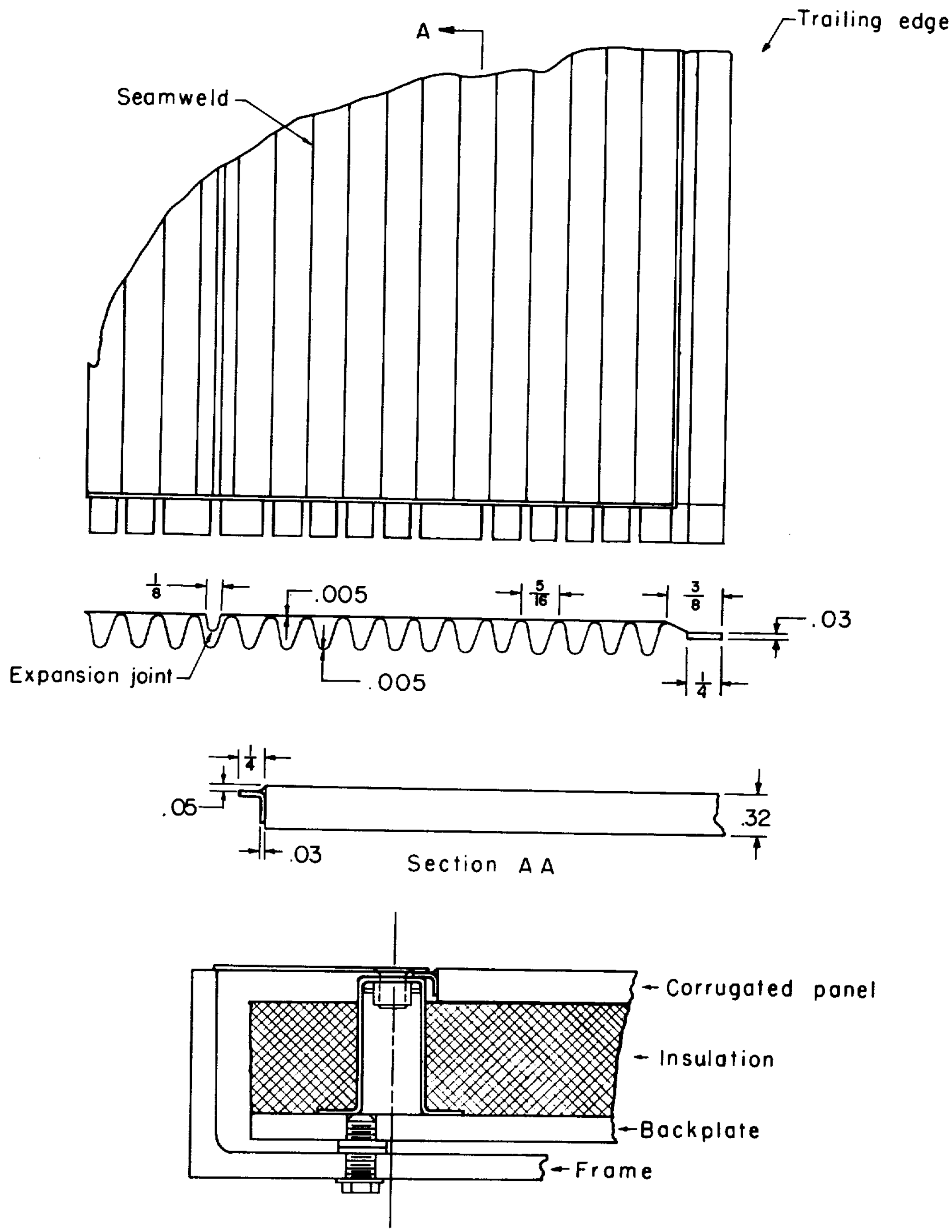


(e) Panel edge condition (3), rounded notches.

Figure 1.- Continued.

[redacted]

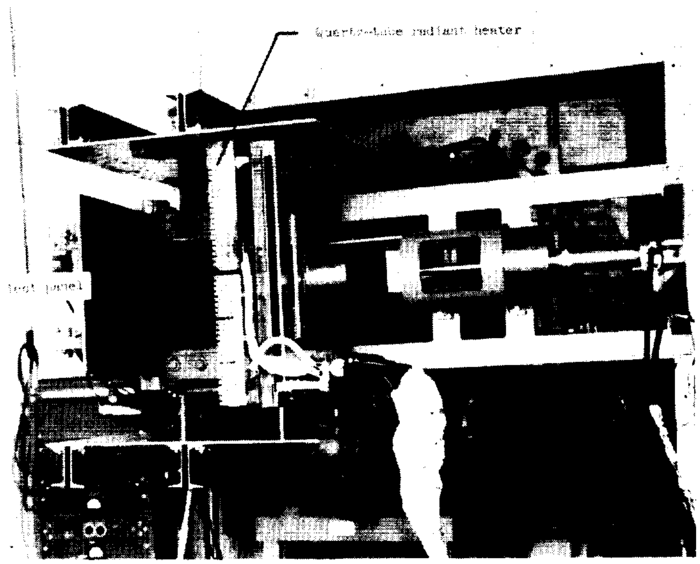
[redacted]



(f) Panel edge condition (4), brazed angle supports.

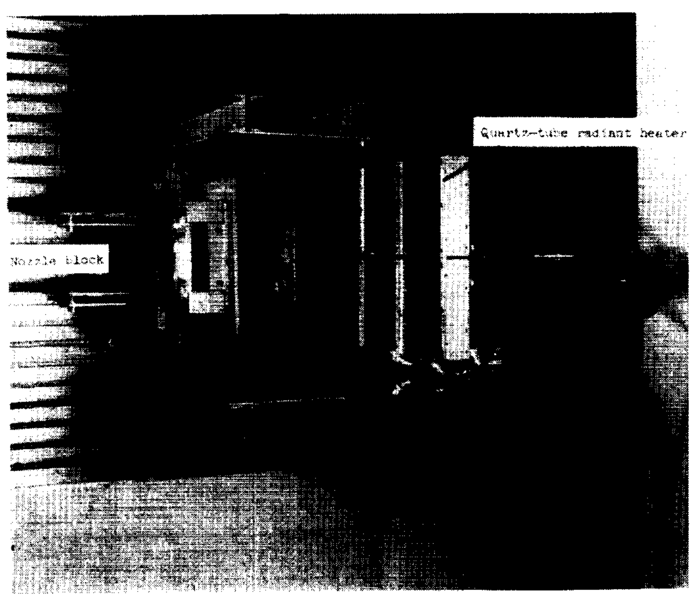
Figure 1.- Concluded.

[redacted]



L-94857.1

(a) View of panel assembly positioned in test fixture at NASA Wallops Station.



L-94078.1

(b) Test fixture mounted on a wall in Langley Structures Research Division.

Figure 2.- Test fixture.

[redacted]

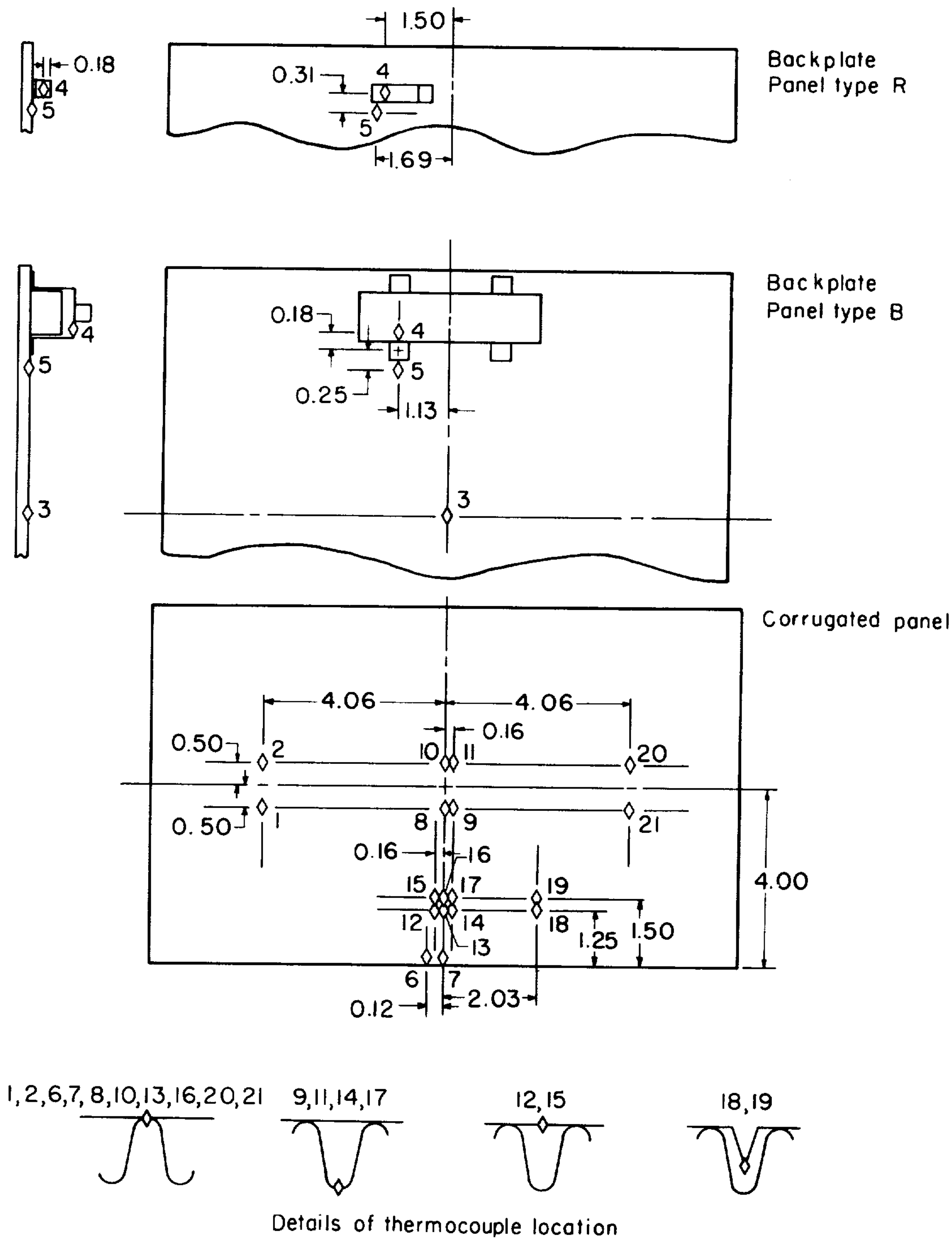


Figure 3.- Typical thermocouple location for panels with either bulk or reflective insulation. Linear dimensions are in inches.

[redacted]

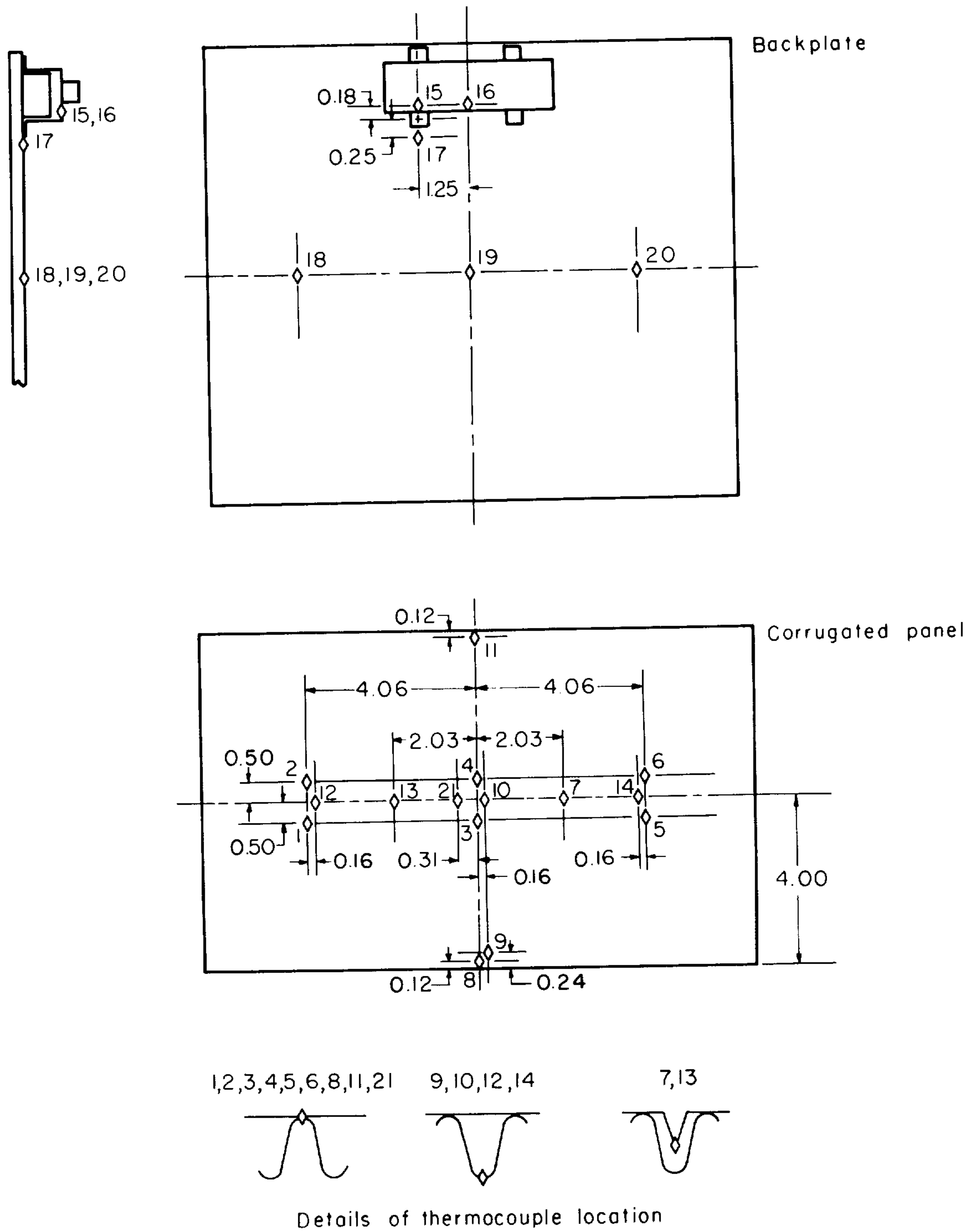
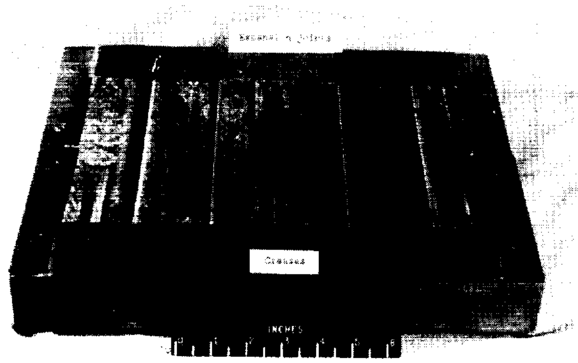
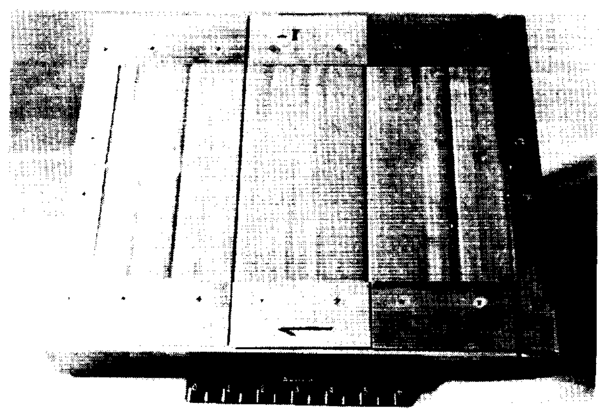


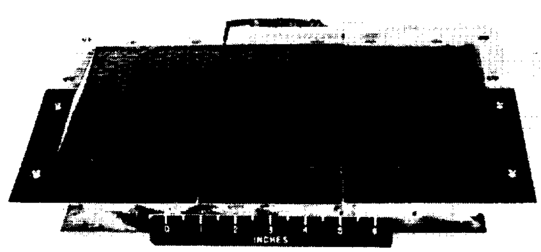
Figure 4.- Thermocouple location for panel B-3, test 21. Linear dimensions are in inches.



(a) Panel B-1 after tests 1 to 5 (maximum skin temperature 1,745° F).



(b) Panel B-3 after tests 11 to 13 (maximum skin temperature 1,675° F).

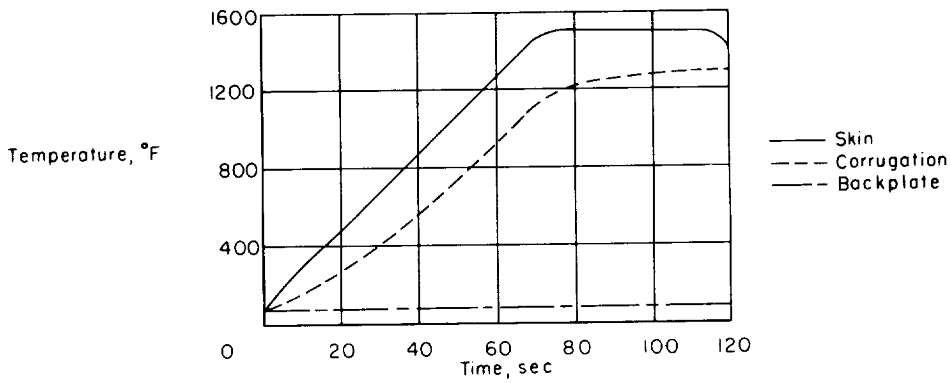


L-59-1931

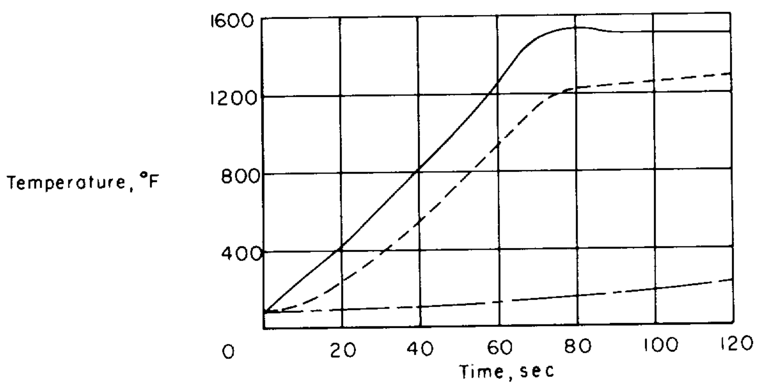
(c) Typical panel B-4 showing small rectangular skin buckles over skin after maximum skin temperature of 1,804° F.

Figure 5.- Photographs showing typical panel skin deformations.

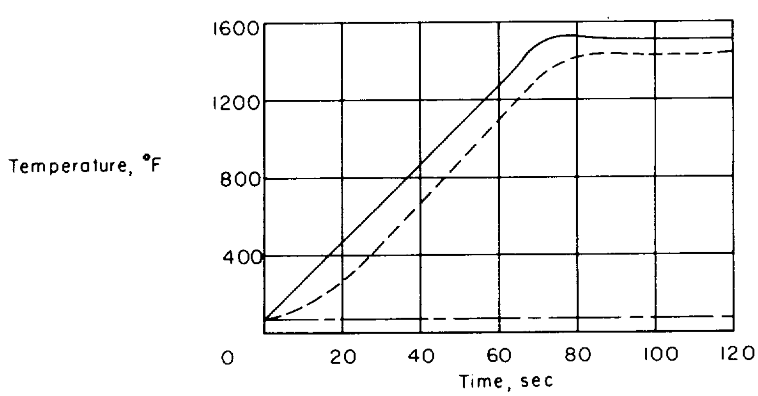
[redacted]



(a) Temperature history for panel B-3, test 21.



(b) Temperature history for panel R-3, test 22.

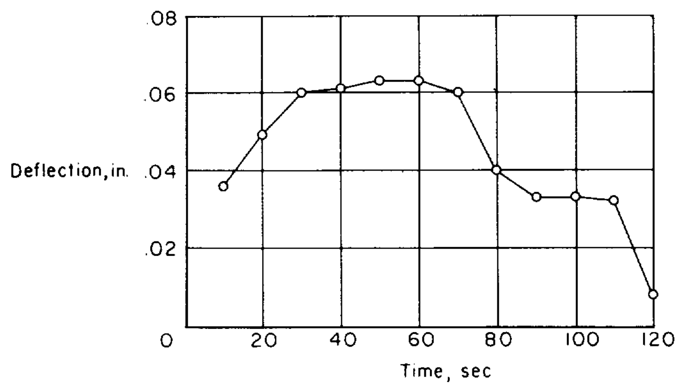


(c) Temperature history for panel B-4, test 23.

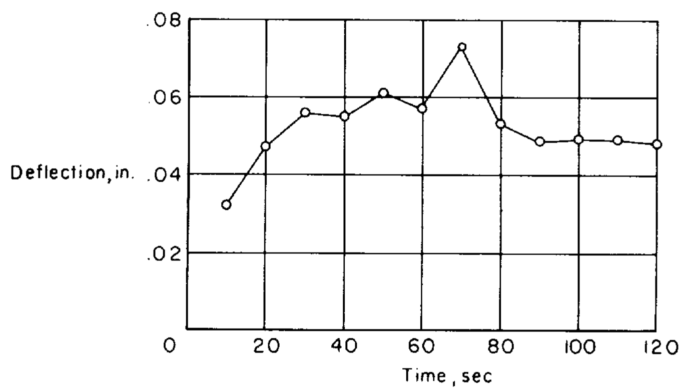
Figure 6.- Typical temperature histories for static radiant-heating tests.

[redacted]

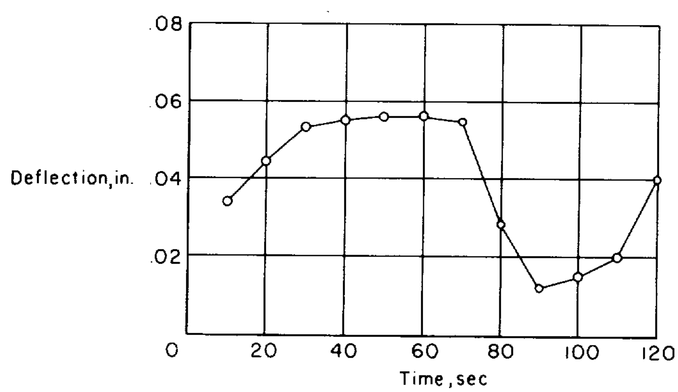
[redacted]



(a) Deflection history for panel B-3, test 21.



(b) Deflection history for panel R-3, test 22.

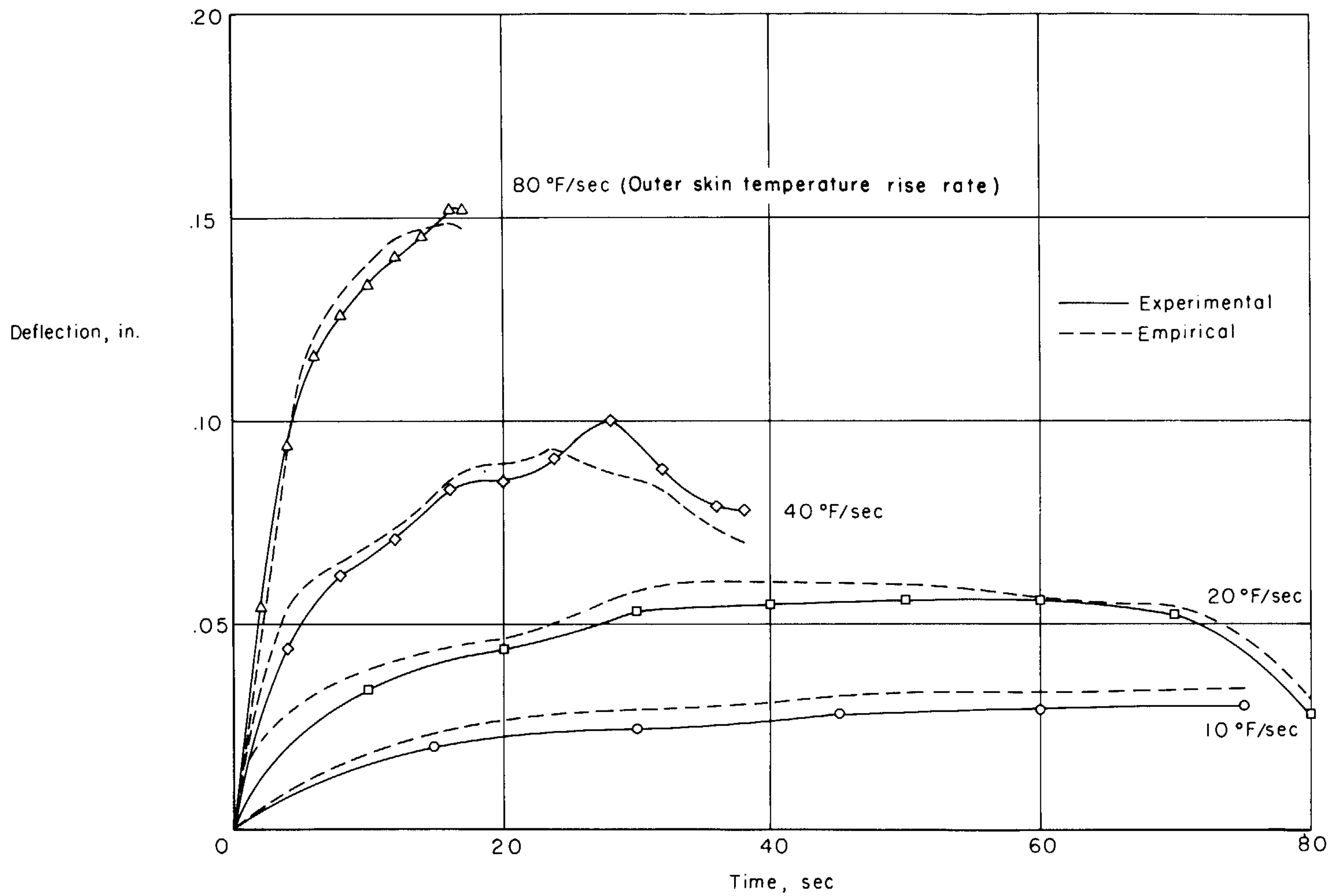


(c) Deflection history for panel B-4, test 23.

Figure 7.- Typical deflectometer data for static radiant-heating tests.

[redacted]

[redacted]

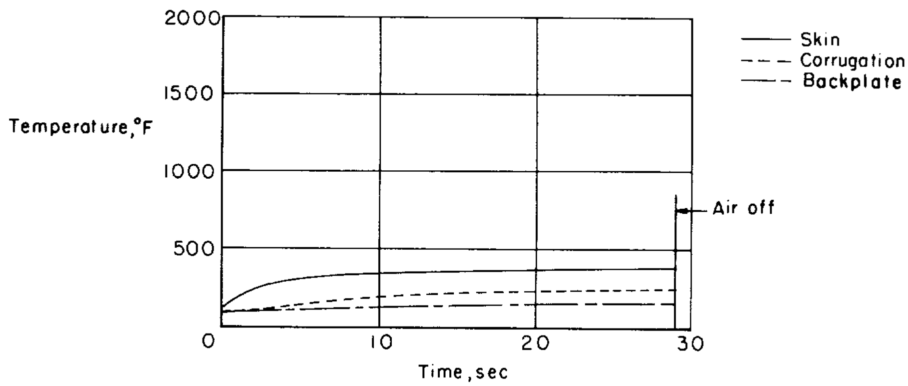


(d) Deflectometer data for static radiant heating tests on panel B-4 at various skin temperature rise rates.

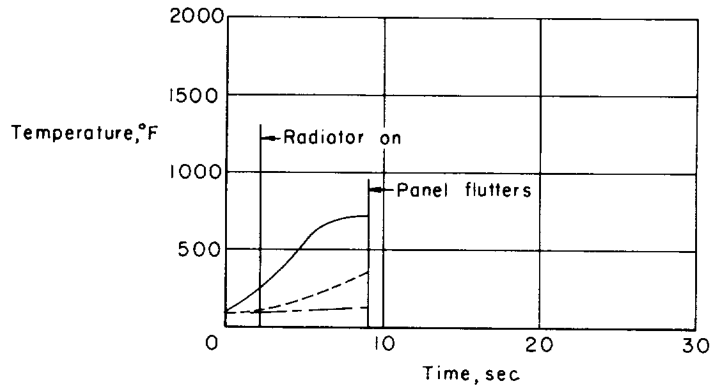
Figure 7.- Concluded.

[redacted]

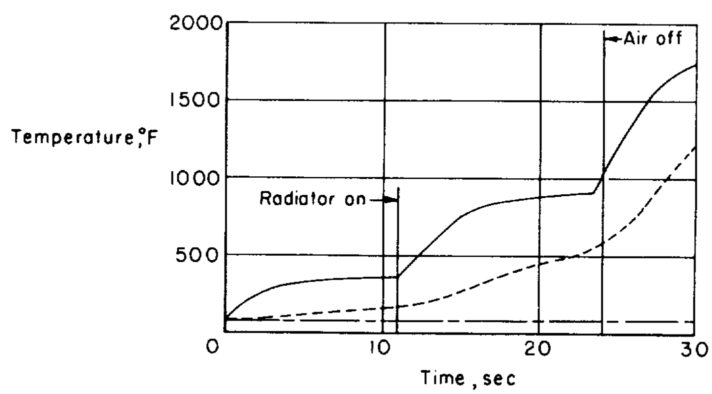
[redacted]



(a) Temperature history for panel R-3, test 28.



(b) Temperature history for panel R-3, test 29.



(c) Temperature history for panel B-4, test 30.

Figure 8.- Temperature histories for the aerodynamic tests.

[redacted]