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INFLUENCE OF SALT AND ELEVATED-TEMPERATURE EXPOSURE ON THE MAXIMUM COMPRESSIVE STRENGTH OF TITANIUM-ALLOY SKIN-STRINGER PANELS

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16. Abstract

The influence of salt and elevated-temperature exposure on the maximum compressive strength of titanium-alloy skin-stringer panels has been investigated. Thirty-five panels were fabricated from Ti-8Al-1Mo-1V titanium alloy by riveting, resistance- and arc-spotwelding, tungsten inert-gas (TIG) fusion welding, and diffusion bonding. One group of panels was tested to failure at room temperature after being coated with a 3.4-percent NaCl solution and exposed at 600° F (590 K) for 1000 hours to develop and grow corrosion cracks. The other group was tested to failure after being heated to 600° F (590 K) from the skin side by a quartz-lamp radiator. Strengths at maximum load were compared to assess the joining techniques, and the results of this study were compared with room-temperature results of a previous study and with results of an existing compressive strength analysis. Hot-salt-stress-corrosion cracks had little effect on panel strengths although considerable tearing and deformation at maximum load appeared to initiate from the cracks. The maximum strengths of the panels tested at elevated temperatures showed little variation (approximately 11 percent) and were consistently lower than the strengths obtained in previous room-temperature tests. These reduced strengths resulted from reductions in material properties at elevated temperature and not from thermal stresses. The magnitude of the maximum strengths of the panels was reasonably predicted by the local-crippling compressive strength analysis.

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SUMMARY

The influence of salt and elevated-temperature exposure on the maximum compressive strength of titanium-alloy skin-stringer panels has been investigated. Thirty-five skin-stringer panels were fabricated from Ti-8Al-1Mo-1V titanium alloy by riveting, resistance- and arc-spotwelding, tungsten inert-gas (TIG) fusion welding, and diffusion bonding. The panels were representative of aircraft wing and fuselage surfaces. Twenty panels were tested to failure in end compression at room temperature after exposure at 600° F (590 K) in an oven for 1000 hours to develop and grow corrosion cracks. Eighteen of these panels had been coated with a 3.4-percent NaCl solution before elevated-temperature exposure, and two had been left uncoated (no salt) as control specimens. The other 15 uncoated panels were tested to failure after being heated to 600° F (590 K) from the skin side by a quartz-lamp radiator. Strengths at maximum load were determined for each of the panels and were compared in order to assess the merits of the various joining techniques. The results of these tests were also compared with previous room-temperature results and with results calculated from an existing compressive strength analysis.

The presence of hot-salt-stress-corrosion cracks had little effect on panel strength although the considerable tearing and deformation that occurred at maximum load appeared to initiate from the cracks. The maximum strengths for the 15 panels tested at elevated temperatures showed little variation (approximately 11 percent), with diffusion-bonded and arc-spotwelded panels exhibiting the highest and lowest strengths, respectively. The strengths of the panels tested at elevated temperatures were lower than the strengths obtained in previous room-temperature tests. These reduced strengths resulted from reductions in material properties at elevated temperature and not from thermal stresses. The magnitude of the maximum strengths of the panels was reasonably predicted by the local-crippling compressive strength analysis.

INTRODUCTION

Titanium alloys are being considered increasingly for application in structural components of both subsonic and supersonic aircraft. For a supersonic transport application, materials screening tests such as those in references 1 and 2 have indicated that titanium alloys are prime candidates. However, it is well known that some titanium alloys are susceptible to hot-salt-stress corrosion. Several studies (e.g., ref. 3) have been made to determine the severity of hot-salt-stress-corrosion damage on these titanium alloys, but little effort has been made to determine the effect corrosion damage may have on the performance of fabricated structural components. Cracking would be expected to affect tensile performance more severely than compressive performance. However, many structural components are loaded in compression, and questions are raised as to the effects of cracks on the compressive performance of these components. Also, the performance of these structural components at elevated temperatures is of interest. Therefore, a research program was initiated to study the influence of salt and elevated-temperature exposure on the compressive strength of titanium-alloy skin-stringer panels fabricated by several different methods.

Thirty-five skin-stringer panels of essentially the same panel configuration were fabricated from titanium-alloy sheet by riveting, resistance- and arc-spotwelding, tungsten inert-gas (TIG) fusion welding, and diffusion bonding to join stringers to the skin. The design, fabrication, and material used in constructing the panels were the same as those used for the panels in reference 4. The fabrication procedures caused residual stresses to appear in the joints and bend radii of the stringers of each panel. In a conducive environment of salt and elevated temperature, these stresses could cause salt-stress-corrosion cracks to occur in the material. Twenty panels were tested to failure in end compression at room temperature after exposure at 600° F (590 K) in an oven for 1000 hours to develop and grow corrosion cracks. Eighteen of these panels had been coated with a 3.4-percent NaCl solution before elevated-temperature exposure, and two had been left uncoated (no salt) as control specimens. Another group of 15 uncoated panels were heated to 600° F (590 K) from the skin side by a quartz-lamp radiator before testing to failure in end compression.

Strengths at maximum load were determined for each of the panels tested and a comparison was made of the panel strengths for the various fabrication techniques. Comparisons were also made with room-temperature panel strengths reported in reference 4. The salt-coated panels were examined for corrosion cracks after the maximum-load tests, and the influence of the corrosion cracks on panel strength and failure behavior was assessed.

SYMBOLS

The physical quantities defined in the present study are given both in U.S. Customary Units and in the International System of Units (SI). (See ref. 5.) Factors relating the two systems are given in the appendix.

A — cross-sectional area of skin-stringer panel, in^2 (m^2)

b_A — width of attachment flange of stringer (fig. 1), in. (m)

b_F — width of outstanding flange of stringer (fig. 1), in. (m)

b_O — geometric fastener offset, distance from center line of attachment flange to center line of stringer (fig. 1), in. (m)

b_S — stringer spacing (fig. 1), in. (m)

b_W — depth of web of stringer (fig. 1), in. (m)

P_{max} — maximum load, kips (N)

t_F — flange thickness (fig. 1), in. (m)

t_S — skin thickness (fig. 1), in. (m)

t_W — stringer thickness (fig. 1), in. (m)

σ_{max} — maximum compressive strength (that is, average stress at maximum load), ksi (N/m^2)

TESTS

Material and Test Specimens

The material used to fabricate the skin-stringer panels was Ti-8Al-1Mo-1V titanium-alloy sheet. Two heat treatment conditions were investigated: duplex and triplex anneal. The nominal sheet thicknesses and the procedures for heat treating the material are given in table I.

The configuration of the skin-stringer panels is shown in figure 1. This configuration is identical to that of the panels described in reference 4, and the panels in the present investigation were fabricated from the same sheets of material as used in reference 4. The panels were constructed with Z-, L-, and T-stringers and had the following nominal parameters: $b_S/t_S = 30$ and $b_W/t_W = 30$, with $t_W/t_S = 0.8$ for duplex-annealed panels and $t_W/t_S = 1.0$ for triplex-annealed panels. These proportions were selected so that local buckling of panels tested at room temperature would occur in the skin between stringers at a calculated stress of 75 ksi (520 MN/m^2), 12 percent below the calculated nominal crippling-failure stress of 85 ksi (590 MN/m^2). Thus, the various types of joints would be bent and twisted by the buckling distortions to test their integrity up to the maximum compression load.

The stringers were joined to the face sheet by the following five methods: riveting, resistance-spotwelding, arc-spotwelding, tungsten inert-gas (TIG) fusion welding, and diffusion bonding. Table II gives the dimensions and mass of the 35 panels of the present investigation. The design and fabrication procedures used for constructing the panels are discussed in appendix B of reference 4.

Test Procedures

Material tests.- The procedures are described in reference 4 for standard room-temperature stress-strain tests that were performed on coupons of each of the sheets used in the construction of the panels. In the present investigation additional compression specimens were tested after exposure at 600° F (590 K) to determine the effect elevated-temperature exposure had on the room-temperature properties of the material.

Room-temperature strength tests of salt-coated panels after elevated-temperature exposure.- A group of 20 panels were tested in end compression in the 1 200 000-pound-capacity (5.34-MN) universal static testing machine at the Langley Research Center (see fig. 2). Prior to testing, the ends of each panel were checked for parallelism and flatness to insure uniform loading through the panel. Eighteen of these skin-stringer panels were dipped in a 3.4-percent (by weight) NaCl solution and dried in an oven at 200° F (370 K). As a result of the dipping, a moderately heavy salt coating formed on and around the joints and bend radii of the stringers. In these areas residual stresses are present from the fabrication processes. References 6 and 7 have indicated that residual stresses in formed parts (such as stringers) are of sufficient magnitude to produce salt-stress-corrosion cracks if the parts are placed in a conducive environment of salt and elevated temperature. The 18 salt-coated panels were placed in a circulating air oven at 600° F (590 K) at sea-level atmosphere for 1000 hours in order to develop and grow stress-corrosion cracks. Two uncoated panels were also placed in the oven for the 1000-hour exposure. After the elevated-temperature exposure, the panels were removed from the oven, allowed to cool at room temperature, and washed in distilled water to remove the salt. After air drying, the panels were ready for testing.

A load of 1 kip (4.4 kN) was used to preset each panel and check the recording system. The panels were then loaded to failure at a rate of 10 kips per minute (0.7 kN/sec).

In order to examine the salt-coated panels for cracks, the tested panels were sectioned into small representative components. These components were etched in a solution consisting of 1 part concentrated hydrofluoric acid (HF), 6 parts hydrogen peroxide (H_2O_2, 30-percent concentration), and 3 parts water, by volume. This etch (ref. 8) has been used in chemical milling of titanium alloys and has proved to be very effective in revealing stress-corrosion cracks (the cracks can be easily seen with little or no magnification and with no additional surface preparation). Specimens to be etched were dipped in the solution at room temperature for 30 seconds, then removed and washed in distilled water.

Elevated-temperature strength tests of uncoated panels.- A group of 15 uncoated panels were instrumented and tested in end compression in the 1 200 000-pound-capacity (5.34-MN) universal static testing machine equipped with a quartz-lamp radiator for elevated-temperature testing (see fig. 3). Data were obtained from two panels for each fabrication process except that duplicate information was not obtained for the diffusion-bonded Z-stringer panels. Before testing, the ends of each panel were checked for parallelism and flatness to obtain uniform loading.

The skin side of the panels was heated by the quartz-lamp radiator (see fig. 3). By using a temperature survey on a representative panel, the spacing and number of quartz lamps in the radiator were predetermined to insure a temperature of approximately 600° F (590 K) over most of the skin of the test panels. The stringers were allowed to reach equilibrium temperature. The panels were then loaded to 2 kips (8.90 kN) and initial settings were made in the recording system. The panels were then heated so that the control thermocouple located at the center of the panel skin indicated 600° F (590 K). When the 12 thermocouples monitored at the test site indicated that equilibrium had been reached (approximately 15 minutes), the panels were loaded to failure at a rate of approximately 10 kips per minute (0.7 kN/sec).

Instrumentation

The load for each panel test was recorded at the Langley central digital data recording facility. Data were recorded every 5 kips (22.3 kN) until approximately 50 percent of the predicted maximum load was obtained. The data were then recorded at programed intervals of 3 seconds.

Each panel in the group of 15 uncoated panels tested at elevated temperatures was instrumented with 23 iron-constantan thermocouples to indicate the temperature distribution throughout the panel during a test. The thermocouple located on the center of the panel was used as the control thermocouple and was monitored at the test site along with 11 other thermocouples. This procedure permitted observations of panel temperatures at specific points on the panel and determination of the equilibrium condition. Outputs from the other thermocouples were recorded at the recording facility.

STRENGTH ANALYSIS

The basic panel configuration used in the present investigation (fig. 1) was designed for a local-crippling failure of the skin bays, stringer webs, and outstanding flanges when subjected to compression at room temperature. Riveted and welded connections were designed to preclude tensile failures of the connections and buckling between the rivets.

The analysis for predicting local crippling presented in reference 9 and used in reference 4 for strength analysis of uncoated panels tested at room temperature was also used in the present study to estimate the elevated-temperature crippling strength of the panels. The material property data were also adjusted to concur with the actual measured temperatures on the panel elements, as discussed subsequently in the section entitled "Material Property Tests."

It is reported in reference 4 that two modes of failure occurred in the room-temperature panel tests – namely, local crippling for which the panels were designed and wrinkling which frequently occurs in panels when the stringers have attachment flanges. Although an analysis has been developed for the wrinkling mode of failure (ref. 10), it was not used in the present study. The analysis (ref. 10) was based on experimental data for aluminum panels fabricated with variations in rivet diameter, pitch, and offset from stringer center line, so some modification based on experimental data for titanium-alloy panels would be necessary for it to be applicable herein.

The effect of thermal stresses on maximum compressive strength of the elevated-temperature panels appeared to be negligible as indicated subsequently in the section entitled "Elevated-Temperature Strength Tests of Uncoated Panels."

RESULTS AND DISCUSSION

Material Property Tests

Values of the elastic modulus and compressive yield stress as well as the corresponding tensile properties are listed in table III for each nominal sheet thickness and heat treatment. The values given are averages obtained in reference 4 from the results of four tests per sheet and from one to 14 sheets of material; some elevated-temperature results obtained in the present study are also included.

Examination of the material properties listed in table III indicates little difference in the compressive properties for the two heat treatment conditions. The compressive yield stress of the triplex-annealed sheet averaged 147 ksi (1010 MN/m^2), the individual values ranging to ±2 percent. (See table III(b).) The duplex-annealed sheet displayed an average compressive yield stress of 143 ksi (990 MN/m^2), the individual values ranging to ±7 percent with one exception. The cap material in the diffusion-bonded T-stringer panels indicated a compressive yield stress of 160 ksi (1100 MN/m^2) after exposure to the diffusion-bonding process. Tensile tests of the same cap material indicated a possible embrittlement, as the elongation was only 2.0 percent. The properties of the diffusion-bonded web and skin material did not differ significantly from typical duplex-annealed properties, and the skin material exposed for 1000 hours at 600° F (590 K) showed little change in compressive properties due to the exposure. (See table III(a).)

Elevated-temperature material properties representative of the temperatures observed during the present study were obtained by using data presented in reference 11. Ratios of the elastic-modulus and the compressive-yield-stress values at elevated temperatures to the corresponding values at room temperature are presented in table IV.

Room-Temperature Strength Tests of Salt-Coated Panels After Elevated-Temperature Exposure

Maximum strength.- The maximum compressive strength (σ_{max}) of salt-coated panels exposed for 1000 hours at 600° F (590 K) is shown in figure 4 and table V. In figure 4, the average maximum compressive strengths of the salt-coated panels are compared with the average maximum compressive strengths of the uncoated panels tested at room temperature (ref. 4). It was not expected that panel strength would be significantly reduced even if cracks were present because the panels were loaded in compression. In fact, with the exception of the diffusion-bonded and resistance-spotwelded specimens, the average maximum strengths of the exposed salt-coated panels showed an increase of approximately 5 percent over the average maximum strengths of the room-temperature panels (ref. 4). This increase in strength may be due to a partial stress relief of residual stresses. (The presence and relief of residual stresses is discussed in ref. 4.) It is therefore likely that 1000 hours at 600° F (590 K) resulted in a partial stress relief for the exposed panels. The increase in strength was not obtained for the diffusion-bonded panels because the high temperatures required in the bonding process (described in appendix B of ref. 4) precluded residual stresses.

All exposed diffusion-bonded panels, both salt-coated and uncoated, showed a 2 to 3 percent decrease in maximum strength compared with the maximum strength of the diffusion-bonded panels of reference 4. (See fig. 4.) This reduction could be the result of material degradation caused by the elevated-temperature exposure. This type of reduction was noted in reference 12 as a slight aging effect on the titanium alloy. If aging occurred, then it occurred in all the panels exposed for 1000 hours at 600° F (590 K) but was not apparent in the maximum-strength data because the stress relief was of a magnitude large enough to offset the aging effect.

Effects of stress-corrosion cracks on panel failure.- An examination of the salt-coated panels which had failed revealed that considerable deformation and tearing had occurred in the stringers. This type of failure was not obtained in the uncoated panels tested at room temperature (ref. 4) or at elevated temperature (as described in the next section). Salt-coated panels representative of all fabrication processes except diffusion bonding exhibited the deformation and tearing. The failures of the diffusion-bonded panels were the same as those reported in reference 4 for the room-temperature panels.

Typical failures for the resistance-spotwelded and TIG-welded panels are shown in figure 5. The tearing initiated in the bend radii of the stringers and in some panels progressed through the flanges. The residual tensile stresses, which resulted from the forming operation (see ref. 6), were located on the inner side of the bend of the stringers. Sections were cut from the panels which exhibited the most pronounced tearing and were etched and examined for stress-corrosion cracks. A photograph of typical sections taken from the failed salt-coated panels is shown in figure 6. A closeup of several of these sections (fig. 7) reveals salt-stress-corrosion cracks in the vicinity of the torn area. Tearing failure of the stringers is assumed to have initiated in the area exhibiting stress-corrosion cracks. It is evident, as noted previously, that the cracks do not significantly affect the maximum compressive strength of the panel but do initiate considerable tearing and deformation of the material in the cracked regions at panel failure.

Elevated-Temperature Strength Tests of Uncoated Panels

Temperature distribution.- A typical temperature distribution for one of the uncoated skin-stringer panels tested at elevated temperatures is shown in figure 8. Most of the skin was within 15° F of 600° F (within 10 K of 590 K), with the center portion of the skin surface within 3° F of 600° F (within 2 K of 590 K). The lower temperature at each end is due to the heat sink created by the massive heads of the testing machine (see fig. 2). However, since failure occurred in the center of the panels, the temperature distribution in the panel was satisfactory.

Maximum strength.- Results of the elevated-temperature tests on the group of 15 uncoated panels are presented in table VI and are also shown in figure 9. The diffusion-bonded panel exhibited the greatest compressive strength, about 70 ksi (482 MN/m^2). The arc-spotwelded panels indicated the lowest strength, about 62 ksi (427 MN/m^2). The 11-percent difference between the strongest and weakest panels indicates that relatively little strength differences were obtained among the five fabrication methods for elevated-temperature applications up to 600° F (590 K).

A comparison of the average maximum strengths of the skin-stringer panels at 600° F (590 K) from the present investigation with the average maximum strengths of similar skin-stringer panels at room temperature (ref. 4) is shown in figure 9. The maximum difference of 29 percent was obtained in the strengths of the diffusion-bonded T-stringer panel; the minimum difference of 13 percent was for the arc-spotwelded panels.

The experimental and predicted strengths of uncoated panels for both room-temperature and elevated-temperature tests are shown in table VII. The agreement between the experimental and predicted maximum strengths of the elevated-temperature panels was comparable with that obtained for the room-temperature panels of reference 4. The same local-crippling analysis was utilized in predicting both room-temperature and elevated-temperature strengths. Although thermal stresses existed in the elevated-temperature panels at the initiation of the tests, the influence of these stresses on maximum strength appeared to be negligible, and the local-crippling analysis used for room-temperature panel (ref. 4) appears reasonable for predicting the maximum strength of elevated-temperature panels. Therefore, the reduction in strength of the panels at 600° F (590 K) from the room-temperature strength (ref. 4) is largely the result of reduction of material properties at elevated temperature.

An examination of the tested panels indicates a general similarity between the failures of the elevated-temperature panels in the present study and the room-temperature panels in reference 4. Typical failures of panels tested at elevated temperatures are shown in figure 10. It appears that local buckling occurred prior to failure in all tests, although some panels failed in the wrinkling mode as shown in reference 4. Because local buckling alleviates thermal stresses (ref. 13), the presence of thermal stresses in the panels reported in this investigation had no significant effect on maximum compressive strength.

CONCLUDING REMARKS

The influence of salt and elevated-temperature exposure on the maximum compressive strength of titanium-alloy skin-stringer panels has been investigated. Panel joining methods included riveting, resistance- and arc-spotwelding, tungsten inert-gas (TIG) welding, and diffusion bonding.

Salt-coated panels that were exposed for 1000 hours at 600° F (590 K) developed salt-stress-corrosion cracks in the bend radii of the stringers where residual stresses due to fabrication were present. The cracks did not affect the maximum compressive strength of the panels but did initiate considerable tearing and deformation of the material in the cracked regions at failure.

The maximum strengths for panels tested at 600° F (590 K) showed little variation (approximately 11 percent), with diffusion-bonded and arc-spotwelded panels exhibiting the highest and lowest strengths, respectively. The reduced strength at elevated temperature, as compared with the strength at room temperature, was due to the reduction in material properties at elevated temperature. There was no apparent effect of thermal stresses on the maximum compressive strength of the panels. The maximum strength of the panel could be reasonably predicted by local-crippling analysis utilizing material properties corresponding to the appropriate temperatures of the panel elements.

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National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 16, 1969.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures in Paris, October 1960. Factors required for converting the U.S. Customary Units used herein to the International System of Units (SI) (ref. 5) are given in the following table:

Physical quantity	U.S. Customary Unit	Conversion factor (*)	SI Unit (**)
Area	in^2	6.4516×10^{-4}	$meters^2$ (m^2)
Force	kip	4.44822×10^{3}	newtons (N)
Length	in.	0.0254	meters (m)
Mass	lbm	0.4536	kilograms (kg)
Stress	ksi	6.895×10^{6}	$newtons/meter^2$ (N/m^2)
Temperature . . .	^{o}F	$\frac{5}{9}(F + 459.67)$	Kelvins (K)

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

**Prefixes to indicate multiples of units are as follows:

Prefix	Multiple
giga (G)	10^{9}
mega (M)	10^{6}
kilo (k)	10^{3}
centi (c)	10^{-2}
milli (m)	10^{-3}

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TABLE I.- DESCRIPTION OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET AND HEAT TREATMENTS

Condition	Nominal thickness		Heat treatment (a)
	in.	mm	
Duplex-annealed sheet	0.050	1.30	Mill-annealed[b] plus 15 minutes at 1450° F (1060 K) with an air cool
	.064	1.60	
Triplex-annealed sheet	.050	1.30	Mill-annealed[b] plus 5 minutes at 1850° F (1280 K) with an air cool plus 15 minutes at 1375° F (1020 K) with an air cool

[a]Vendor supplied information.

[b]Mill-annealed material is annealed 8 hours at 1450° F (1060 K) and furnace cooled.

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS

(a) Salt-coated panels

U.S. Customary Units													
Test	Panel type	Mass, lbm	Length, in.	Width, in.	A, in^2	b_S, in.	b_W, in.	b_F, in.	b_A, in.	b_O, in.	t_S, in.	t_W, in.	t_F, in.
Duplex-annealed panels													
1	Riveted	2.994	13.72	10.20	1.351	1.95	1.33	0.55	0.42	0.24	0.068	0.050	0.050
2		3.003	13.72	10.20	1.350	1.95	1.32	.55	.42	.24	.068	.051	.051
3	Resistance-spotwelded	2.974	13.67	10.30	1.378	1.95	1.35	0.54	0.54	0.32	0.065	0.051	0.051
4		3.004	13.72	10.32	1.384	1.95	1.34	.54	.54	.34	.066	.051	.051
5	Arc-spotwelded	3.048	13.70	10.56	1.408	1.95	1.34	0.55	0.55	0.32	0.068	0.052	0.052
6		2.887	13.63	10.55	1.340	1.95	1.30	.55	.55	.33	.068	.048	.048
7	Tungsten inert-gas welded	2.584	13.29	10.45	1.230	1.94	1.32	0.53	---	---	0.063	0.053	0.053
8		2.601	13.27	10.47	1.240	1.94	1.33	.52	---	---	.063	.053	.053
9	Diffusion bonded (Z)	2.869	13.65	10.32	1.332	1.95	1.43	0.53	0.53	0.30	0.065	0.048	0.048
10		2.924	13.62	10.32	1.359	1.94	1.39	.56	.56	.31	.065	.050	.050
11	Diffusion bonded (T)	2.532	13.20	10.27	1.214	1.95	1.29	0.29	---	---	0.062	0.047	0.049
12		2.517	13.65	10.25	1.120	1.95	1.29	.29	---	---	.063	.048	.048
[a]13		2.483	13.54	10.24	1.160	1.95	1.29	.29	---	---	.063	.047	.049
[a]14		2.501	13.56	10.27	1.170	1.95	1.29	.29	---	---	.063	.048	.049
Triplex-annealed panels													
1	Riveted	1.532	9.48	7.21	0.935	1.35	1.35	0.54	0.44	0.25	0.047	0.046	0.046
2		1.532	9.46	7.18	.938	1.35	1.35	.54	.42	.24	.047	.047	.047
3	Resistance-spotwelded	1.445	9.50	7.33	0.970	1.35	1.36	0.53	0.54	0.31	0.046	0.047	0.047
4		1.482	9.47	7.35	.990	1.35	1.36	.53	.54	.31	.042	.047	.047
5	Tungsten inert-gas welded	1.203	9.60	7.50	0.794	1.34	1.35	0.54	---	---	0.045	0.042	0.042
6		1.260	9.97	7.50	.800	1.34	1.34	.54	---	---	.043	.041	.041

[a]Panel left uncoated as control specimen.

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS – Continued

(a) Salt-coated panels – Concluded

SI Units

Test	Panel type	Mass, kg	Length, mm	Width, mm	A, cm^2	b_S, mm	b_W, mm	b_F, mm	b_A, mm	b_O, mm	t_S, mm	t_W, mm	t_F, mm
Duplex-annealed panels													
1	Riveted	1.36	348	259	8.70	49.5	33.8	14.0	10.7	6.1	1.7	1.3	1.3
2		1.36	348	259	8.70	49.5	33.5	14.0	10.7	6.1	1.7	1.3	1.3
3	Resistance-spotwelded	1.36	347	262	8.90	49.5	33.7	13.7	13.7	8.1	1.7	1.3	1.3
4		1.36	348	262	8.90	49.5	34.0	13.7	13.7	8.6	1.7	1.3	1.3
5	Arc-spotwelded	1.38	348	268	9.10	49.5	33.7	14.0	14.0	8.1	1.7	1.3	1.3
6		1.31	347	268	8.65	49.5	33.0	14.0	14.0	8.4	1.7	1.2	1.2
7	Tungsten inert-gas welded	1.17	338	266	7.94	49.2	33.5	13.5	---	---	1.6	1.3	1.3
8		1.18	338	266	8.00	49.2	33.8	13.2	---	---	1.6	1.3	1.3
9	Diffusion bonded (Z)	1.30	346	262	8.57	49.5	36.3	13.5	13.5	7.6	1.7	1.2	1.2
10		1.32	346	262	8.77	49.2	35.3	14.2	14.2	7.9	1.7	1.3	1.3
11	Diffusion bonded (T)	1.15	335	261	7.83	49.5	32.8	7.4	---	---	1.6	1.2	1.2
12		1.14	346	260	7.22	49.5	32.8	7.4	---	---	1.6	1.2	1.2
[a]13		1.12	344	260	7.47	49.5	32.8	7.4	---	---	1.6	1.2	1.2
[a]14		1.13	344	261	7.55	49.5	32.8	7.4	---	---	1.6	1.2	1.2
Triplex-annealed panels													
1	Riveted	0.694	241	183	6.04	34.3	34.3	13.7	11.2	6.6	1.2	1.2	1.2
2		.694	241	182	6.04	34.3	34.3	13.7	10.7	6.1	1.2	1.2	1.2
3	Resistance-spotwelded	0.655	242	186	6.25	34.3	34.5	13.5	13.4	7.9	1.2	1.2	1.2
4		.670	241	186	6.38	34.3	34.5	13.5	13.4	7.9	1.2	1.2	1.2
5	Tungsten inert-gas welded	0.545	244	191	5.12	34.0	34.3	13.7	---	---	1.1	1.1	1.1
6		.571	254	191	5.16	34.0	34.0	13.7	---	---	1.1	1.1	1.1

[a]Panel left uncoated as control specimen.

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS – Continued

(b) Uncoated panels

U.S. Customary Units													
Test	Panel type	Mass, lbm	Length, in.	Width, in.	A, in^2	b_S, in.	b_W, in.	b_F, in.	b_A, in.	b_O, in.	t_S, in.	t_W, in.	t_F, in.
Duplex-annealed panels													
1	Riveted	2.999	13.70	10.20	1.350	1.95	1.34	0.54	0.44	0.26	0.068	0.052	0.052
2		3.005	13.72	10.20	1.350	1.95	1.34	.56	.44	.27	.068	.051	.051
3	Resistance-spotwelded	3.010	13.68	10.33	1.390	1.95	1.36	0.54	0.55	0.33	0.066	0.051	0.051
4		2.995	13.67	10.33	1.385	1.95	1.35	.54	.54	.32	.065	.051	.051
5	Arc-spotwelded	3.040	13.71	10.57	1.400	1.95	1.36	0.53	0.54	0.37	0.068	0.052	0.052
6		3.063	13.66	10.58	1.420	1.95	1.36	.55	.55	.36	.068	.053	.053
7	Tungsten inert-gas welded	2.601	13.32	10.47	1.230	1.94	1.31	0.52	---	---	0.064	0.052	0.052
8		2.594	13.29	10.45	1.240	1.94	1.31	.52	---	---	.063	.052	.052
9	Diffusion bonded (Z)	2.825	13.35	10.32	1.340	1.96	1.42	0.56	0.57	0.36	0.065	0.049	0.049
10	Diffusion bonded (T)	2.492	13.52	10.25	1.170	1.95	1.31	0.285	---	---	0.063	0.0485	0.049
11		2.585	13.52	10.28	1.210	1.95	1.32	.285	---	---	.067	.0485	.049
Triplex-annealed panels													
1	Riveted	1.503	9.42	7.21	0.922	1.35	1.35	0.55	0.42	0.23	0.045	0.046	0.046
2		1.521	9.45	7.23	.929	1.35	1.35	.54	.43	.15	.044	.046	.046
3	Resistance-spotwelded	1.444	9.45	7.36	0.970	1.34	1.36	0.54	0.54	0.32	0.045	0.046	0.046
4		1.461	9.52	7.36	.970	1.35	1.35	.54	.55	.32	.046	.046	.046

TABLE II.- DIMENSIONS OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SKIN-STRINGER PANELS – Concluded

(b) Uncoated panels – Concluded

SI Units

Test	Panel type	Mass, kg	Length, mm	Width, mm	A, cm^2	b_S, mm	b_W, mm	b_F, mm	b_A, mm	b_O, mm	t_S, mm	t_W, mm	t_F, mm
Duplex-annealed panels													
1	Riveted	1.36	348	259	8.70	49.5	34.0	13.7	11.2	6.6	1.7	1.3	1.3
2		1.36	348	259	8.70	49.5	34.0	14.2	11.2	6.9	1.7	1.3	1.3
3	Resistance-spotwelded	1.36	348	261	8.95	49.5	34.6	13.7	14.0	8.4	1.7	1.3	1.3
4		1.36	348	261	8.95	49.5	34.3	13.7	13.7	8.1	1.7	1.3	1.3
5	Arc-spotwelded	1.38	348	268	9.04	49.5	34.6	13.5	13.7	9.4	1.7	1.3	1.3
6		1.39	347	268	9.15	49.5	34.6	14.0	14.0	9.1	1.7	1.3	1.3
7	Tungsten inert-gas welded	1.18	338	266	7.94	49.2	33.2	13.2	---	---	1.6	1.3	1.3
8		1.18	338	265	8.00	49.2	33.2	13.2	---	---	1.6	1.3	1.3
9	Diffusion bonded (Z)	1.29	340	262	8.65	49.7	36.0	14.2	14.5	9.1	1.7	1.2	1.2
10	Diffusion bonded (T)	1.13	344	260	7.55	49.5	33.2	7.4	---	---	1.6	1.2	1.2
11		1.17	344	261	7.80	49.5	33.6	7.4	---	---	1.7	1.2	1.2
Triplex-annealed panels													
1	Riveted	0.68	239	183	5.95	34.3	34.3	14.0	10.5	5.8	1.1	1.2	1.2
2		.69	240	184	6.00	34.3	34.3	13.7	10.9	3.8	1.1	1.2	1.2
3	Resistance-spotwelded	0.66	240	187	6.25	34.0	34.6	13.7	13.7	8.1	1.1	1.2	1.2
4		.66	242	187	6.25	34.3	34.3	13.7	14.0	8.1	1.2	1.2	1.2

TABLE III.- MATERIAL PROPERTIES OF Ti-8Al-1Mo-1V TITANIUM-ALLOY SHEET

(a) Duplex-annealed sheet

Panel type	Component	Sheet thickness		Yield stress				Tensile strength		Young's modulus				Elongation, percent	
				Tensile		Compressive				Tensile		Compressive			
		in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2	ksi	GN/m^2	2 in. (5 cm)	Uniform
Tungsten inert-gas welded	Stringer	0.050	1.30	134.8	930	146.5	1010	147.9	1020	18 090.0	125.0	18 780.0	129.0	14.0	9.0
	Skin	.064	1.60	----	---	----	----	----	----	-------	----	-------	----	---	---
Riveted[a]	Stringer	0.050	1.30	136.2	940	142.4	980	147.9	1020	17 200.0	119.0	-------	----	14.5	9.5
	Skin	.064	1.60	137.8	950	151.9	1050	150.5	1040	18 100.0	125.0	-------	----	14.0	8.0
Resistance-spotwelded	Stringer	0.050	1.30	130.0	900	133.0	920	146.0	1010	-------	----	-------	----	14.5	10.0
	Skin	.064	1.60	134.0	920	140.0	970	146.0	1010	-------	----	17 790.0	123.0	15.0	11.0
Arc-spotwelded[a]	Stringer	0.050	1.30	136.2	940	142.4	980	147.9	1020	17 200.0	119.0	-------	----	14.5	9.5
	Skin	.064	1.60	137.8	950	151.9	1050	150.5	1040	18 100.0	125.0	-------	----	14.0	8.0
Diffusion bonded (Z)	Stringer	0.050	1.30	128.3	880	137.2	950	139.0	960	18 040.0	125.0	18 460.0	127.0	20.5	14.0
	Skin	.064	1.60	132.1	910	144.6	1000	142.8	980	18 500.0	128.0	19 000.0	131.0	18.0	15.0
Diffusion bonded (T)	Cap	0.050	1.30	138.0	950	160.0	1100	139.8	960	20 000.0	138.0	20 300.0	140.0	2.5	2.0
	Web	.050	1.30	127.4	880	138.2	950	139.0	960	18 500.0	128.0	19 050.0	131.0	17.0	10.0
	Skin	.064	1.60	134.0	920	144.0	990	145.0	1000	18 600.0	128.0	19 900.0	137.0	15.0	10.0
	Skin[b]	.065	1.65	----	---	150.7	1040	----	----	-------	----	18 500.0	127.0	---	---
	Skin[c]	.065	1.65	----	---	146.2	1010	----	----	-------	----	18 480.0	127.0	---	---

[a]Riveted and arc-spotwelded panels were fabricated from same sheet.
[b]Exposed to 600° F (590 K) for 1000 hours.
[c]Same specimen lot as b with no exposure.

(b) Triplex-annealed sheet

Panel type	Sheet thickness		Yield stress				Tensile strength		Young's modulus				Elongation, percent	
			Tensile		Compressive				Tensile		Compressive			
(a)	in.	mm	ksi	MN/m^2	ksi	MN/m^2	ksi	MN/m^2	ksi	GN/m^2	ksi	GN/m^2	2 in. (5 cm)	Uniform
Tungsten inert-gas welded	0.050	1.30	134.0	920	145.1	1000	148.5	1020	18 350.0	127.0	-------	----	15.0	10.0
	.050	1.30	----	---	[b]146.0	[b]1010	----	----	-------	----	-------	----	---	---
Riveted and resistance-spotwelded[c]	0.050	1.30	139.0	960	148.1	1020	153.0	1050	18 800.0	130.0	18 660.0	129.0	12.0	8.0

[a]Stringers and skin were fabricated from same sheet for each panel type.
[b]Specimen was stress relieved 30 minutes at 1450° F (1060 K) in argon.
[c]Riveted and resistance-spotwelded panels were fabricated from same sheet.

TABLE IV.- EFFECT OF ELEVATED TEMPERATURE ON THE ELASTIC MODULUS AND COMPRESSIVE YIELD STRESS FOR Ti-8Al-1Mo-1V TITANIUM ALLOY

Panel component	Average elevated temperature		Ratio of elastic modulus at elevated temperature to elastic modulus at room temperature	Ratio of compressive yield stress at elevated temperature to compressive yield stress at room temperature
	$^{\circ}F$	K		
Skin	600	590	0.86	0.65
Attachment flange . . .	585	580	.87	.66
Web.	400	480	.90	.73
Outstanding flange . . .	270	405	.94	.82

TABLE V.- EXPERIMENTAL MAXIMUM LOAD AND AVERAGE STRESS AT MAXIMUM LOAD FOR SALT-COATED PANELS AFTER ELEVATED-TEMPERATURE EXPOSURE

Test	Panel type	P_{max}		σ_{max}	
		kips	MN	ksi	MN/m^2
Duplex-annealed panels					
1	Riveted	114.6	0.510	84.7	585
2		117.3	.522	87.0	600
3	Resistance-spotwelded	117.6	0.523	85.4	589
4		118.2	.526	85.5	590
5	Arc-spotwelded	110.2	0.490	78.3	540
6		101.6	.452	75.9	523
7	Tungsten inert-gas welded	105.0	0.467	85.5	590
8		107.6	.478	86.8	598
9	Diffusion bonded (Z)	126.7	0.563	95.0	656
10		130.2	.580	96.0	662
11	Diffusion bonded (T)	109.8	0.488	90.4	623
12		112.2	.499	99.5	686
[a]13		108.0	.480	93.2	642
[a]14		109.5	.487	93.7	646
Triplex-annealed panels					
1	Riveted	76.4	0.340	81.7	563
2		76.2	.339	81.2	560
3	Resistance-spotwelded	83.0	0.369	85.6	591
4		87.5	.399	88.5	611
5	Tungsten inert-gas welded	61.0	0.271	76.9	531
6		59.2	.263	74.0	511

[a]Panel left uncoated as control specimen.

TABLE VI.- EXPERIMENTAL MAXIMUM LOAD AND AVERAGE STRESS AT MAXIMUM LOAD FOR UNCOATED PANELS TESTED AT ELEVATED TEMPERATURES

Test	Panel type	P_{max}		σ_{max}	
		kips	MN	ksi	MN/m^2
Duplex-annealed panels					
1	Riveted	83.2	0.370	61.6	425
2		87.8	.390	65.0	448
3	Resistance-spotwelded	95.9	0.427	68.0	469
4		91.8	.408	66.3	457
5	Arc-spotwelded	86.4	0.384	61.7	426
6		87.8	.390	61.8	426
7	Tungsten inert-gas welded	78.0	0.347	63.4	437
8		79.2	.352	63.8	440
9	Diffusion bonded (Z)	94.2	0.419	70.2	485
10	Diffusion bonded (T)	80.6	0.359	69.0	476
11		81.9	.364	67.7	467
Triplex-annealed panels					
1	Riveted	59.8	0.266	64.8	447
2		61.4	.273	66.2	456
3	Resistance-spotwelded	63.2	0.281	65.2	450
4		65.0	.289	67.0	462

TABLE VII.- EXPERIMENTAL AND PREDICTED STRENGTHS OF UNCOATED PANELS AT ROOM AND ELEVATED TEMPERATURES

(a) Room-temperature tests (ref. 4)

Panel type	Average experimental σ_{max}		Predicted σ_{max}		Percent difference
	ksi	MN/m^2	ksi	MN/m^2	
Duplex-annealed panels					
Riveted	81.0	560	93.0	640	15
Resistance-spotwelded	87.0	600	93.0	640	7
Arc-spotwelded	72.0	495	93.0	640	29
Tungsten inert-gas welded	83.0	575	97.0	670	17
Diffusion bonded (Z)	94.0	650	95.0	655	1
Diffusion bonded (T)	97.0	670	104.0	720	7
Triplex-annealed panels					
Riveted	76.0	525	97.0	670	27
Resistance-spotwelded	85.0	585	97.0	670	14

(b) Elevated-temperature tests

Panel type	Average experimental σ_{max}		Predicted σ_{max}		Percent difference
	ksi	MN/m^2	ksi	MN/m^2	
Duplex-annealed panels					
Riveted	63.3	435	75.0	515	20
Resistance-spotwelded	67.1	465	71.5	495	6
Arc-spotwelded	61.8	425	76.0	525	22
Tungsten inert-gas welded	63.6	440	75.0	515	20
Diffusion bonded (Z)	70.2	485	70.0	483	0
Diffusion bonded (T)	68.4	470	80.0	550	17
Triplex-annealed panels					
Riveted	65.5	450	72.0	495	12
Resistance-spotwelded	66.1	456	72.5	500	10

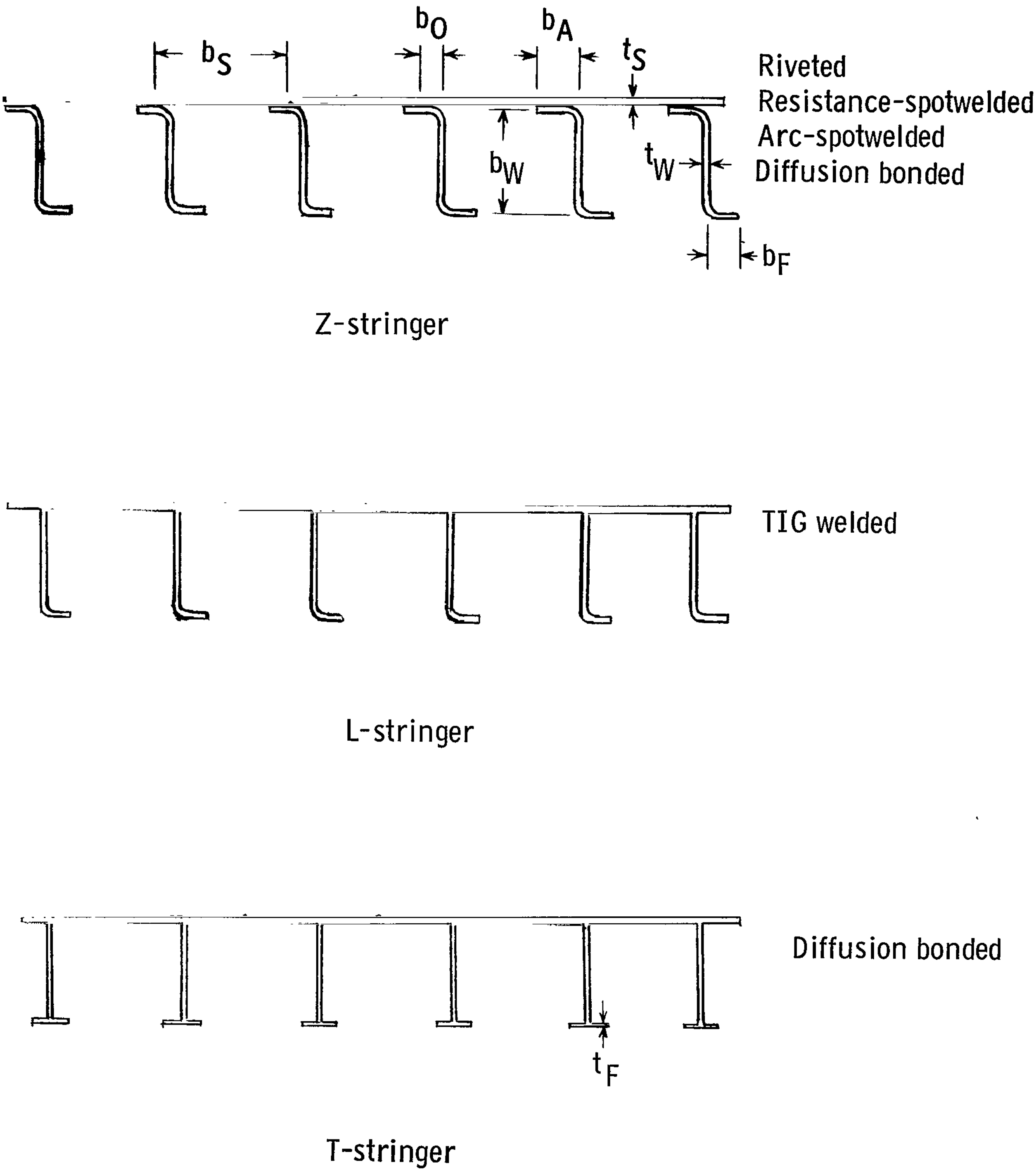
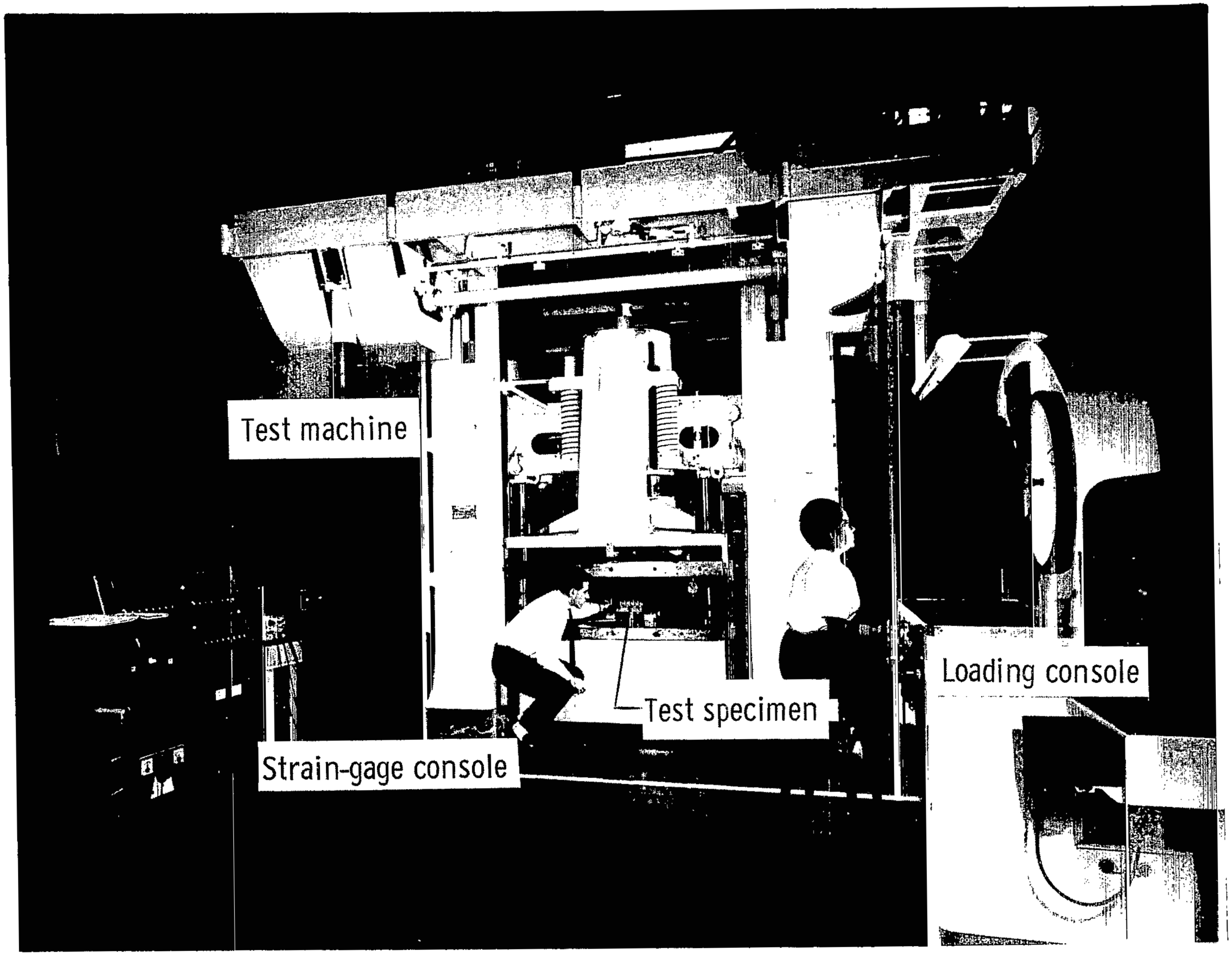


Figure 1.- Cross section of skin-stringer panels.



L-64-5402.1

Figure 2.- Overall test setup.

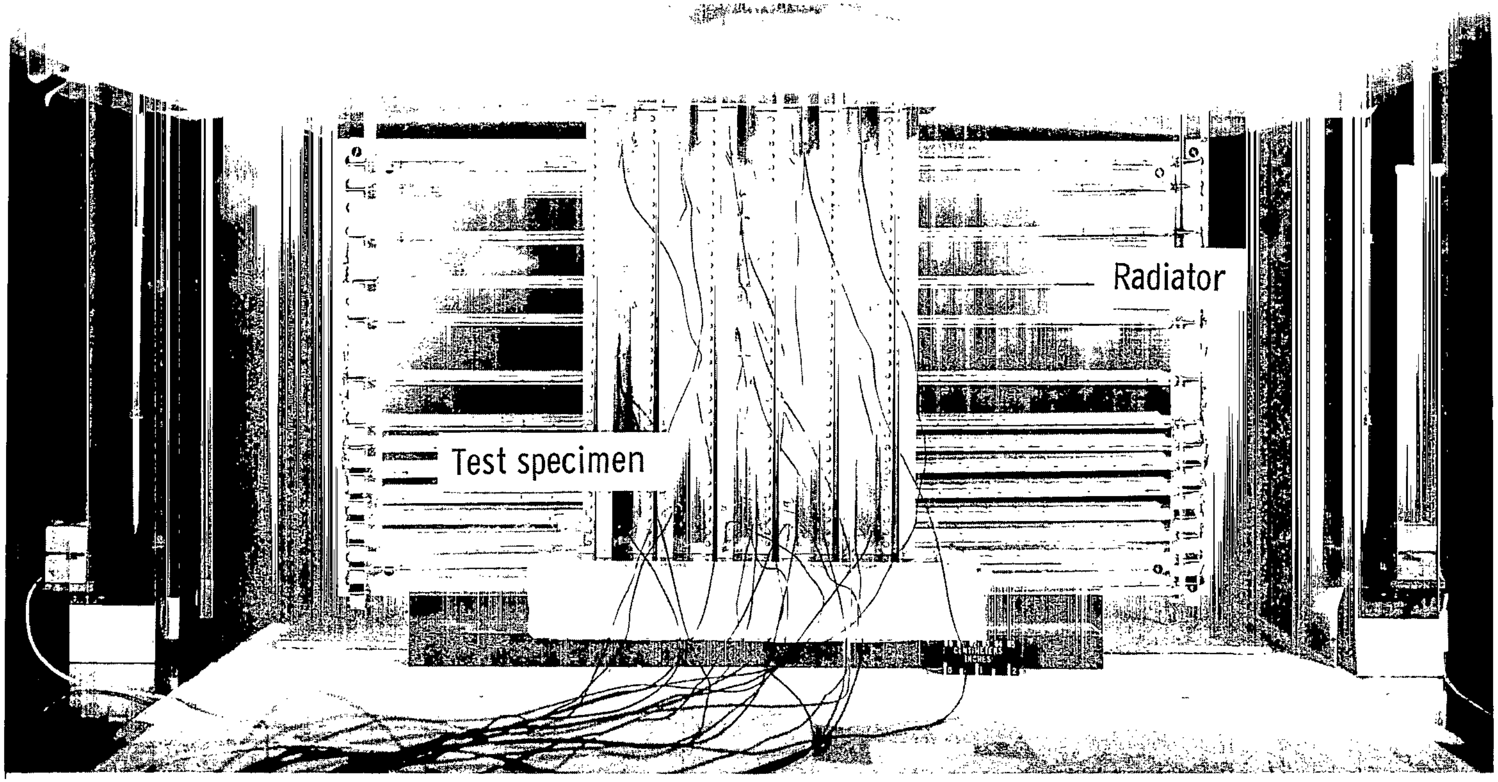


Figure 3.- Closeup of the elevated-temperature test setup. L-66-2029.1

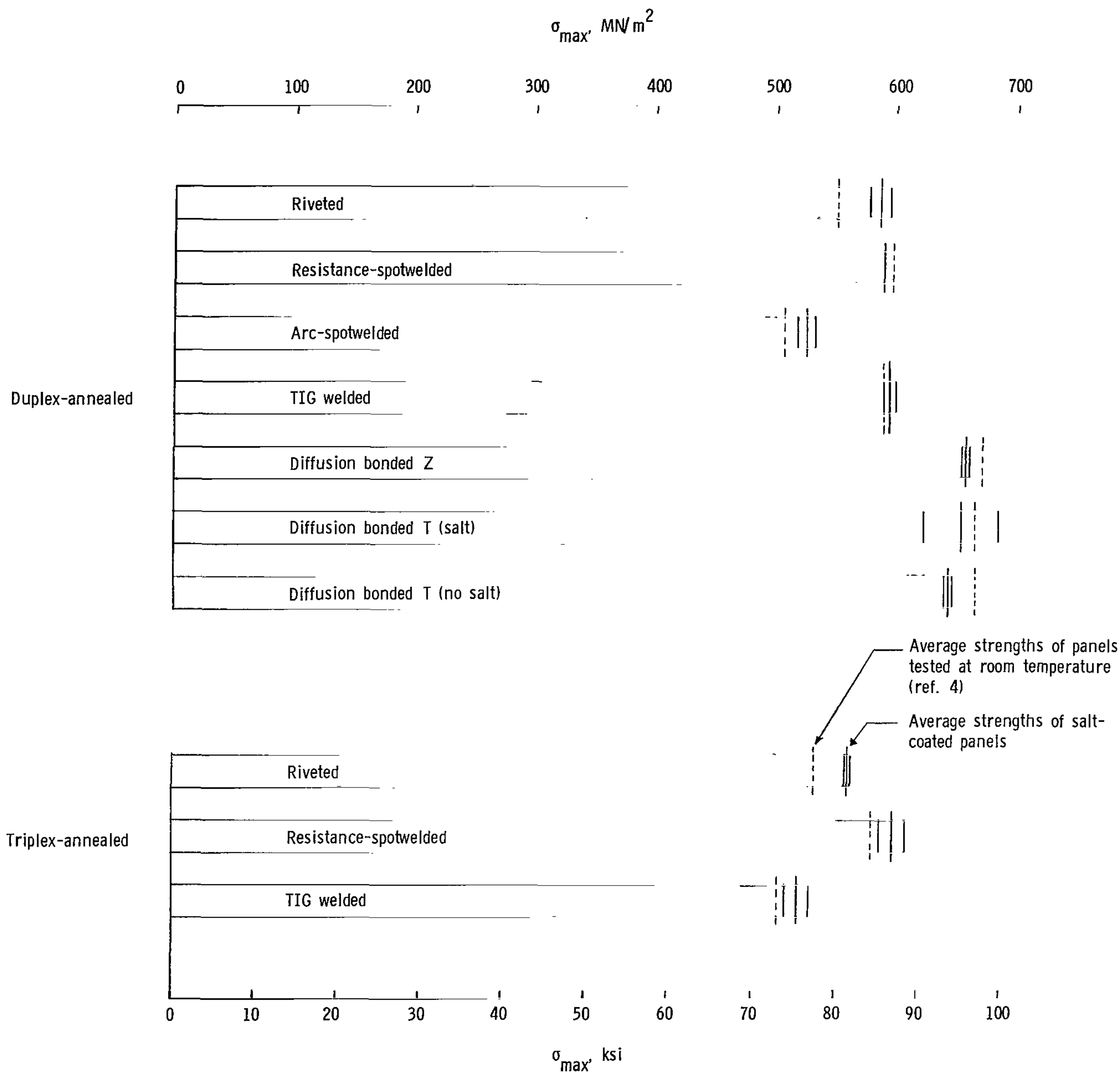
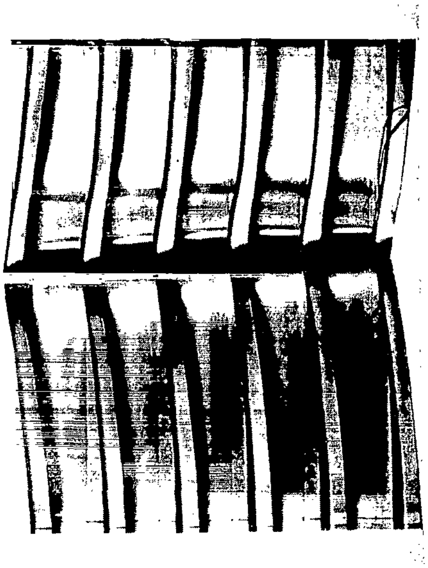
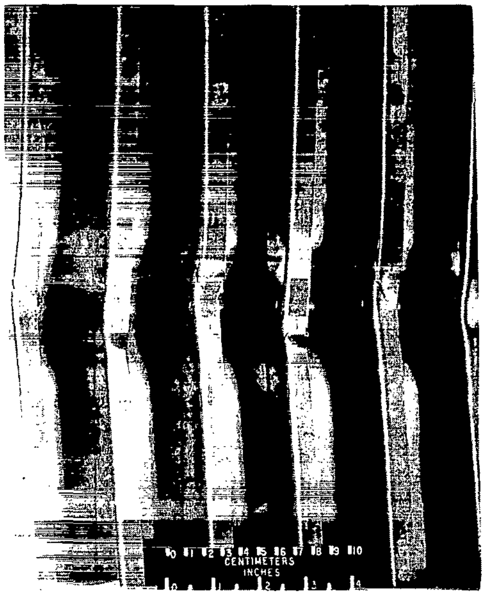


Figure 4.- Comparison of strengths of salt-coated panels with strengths of uncoated panels tested at room temperature in reference 4.

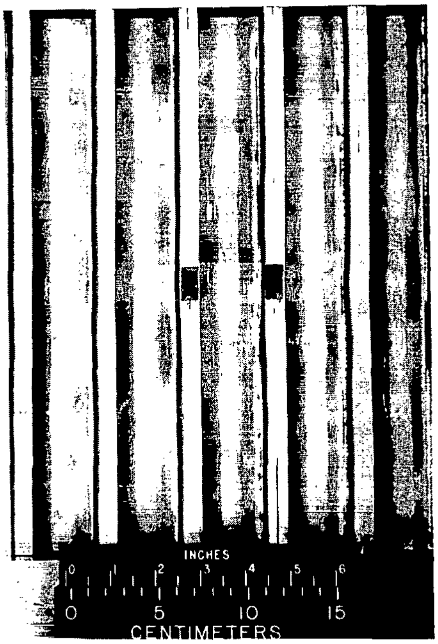


No exposure } (ref. 4)
No salt

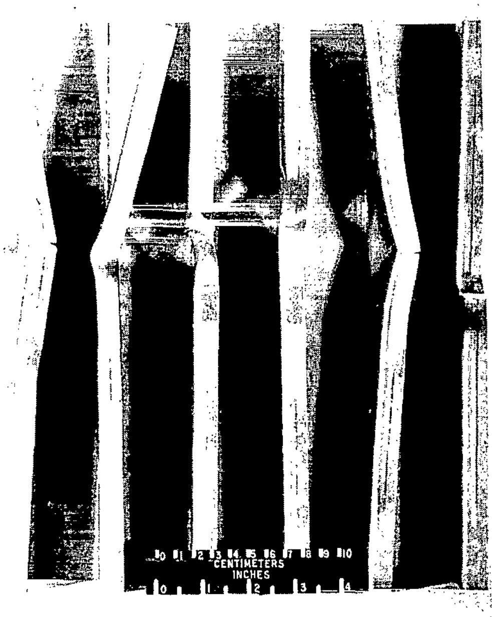


1000-hour exposure at 600°F (590 K)
Salt coated

(a) Resistance-spotwelded panels.



No exposure } (ref. 4)
No salt

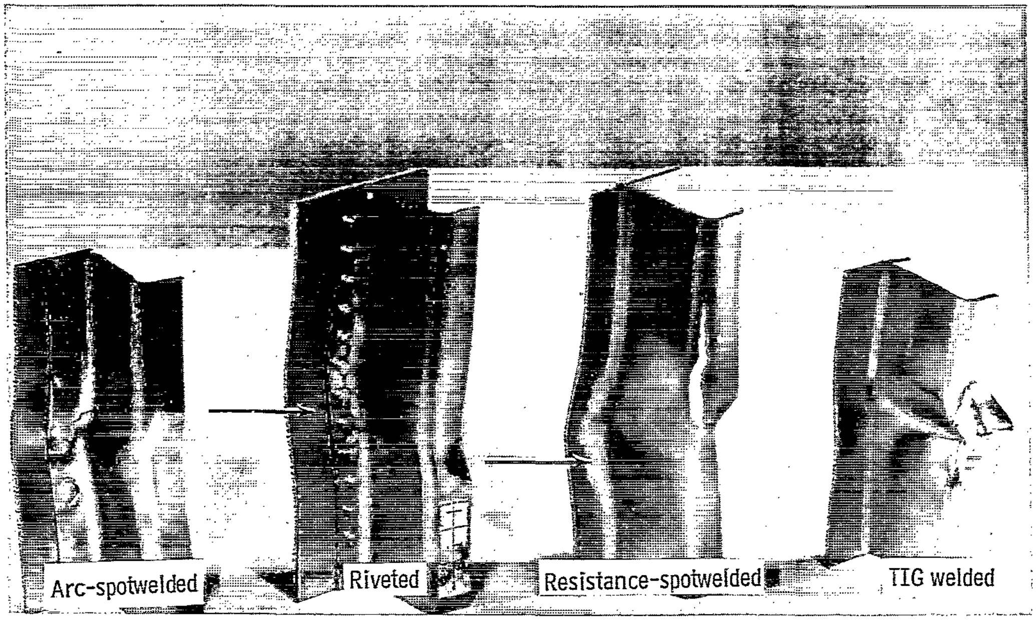


1000-hour exposure at 600°F (590 K)
Salt coated

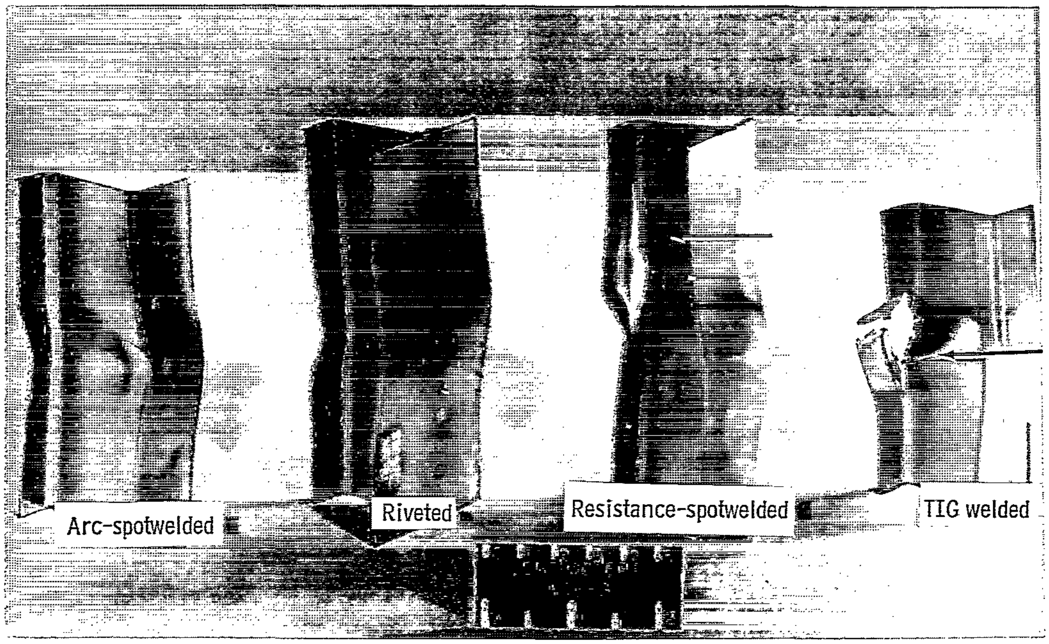
(b) TIG-welded panels.

L-69-5137

Figure 5.- Comparison of failures of panels with and without salt coatings and exposure.

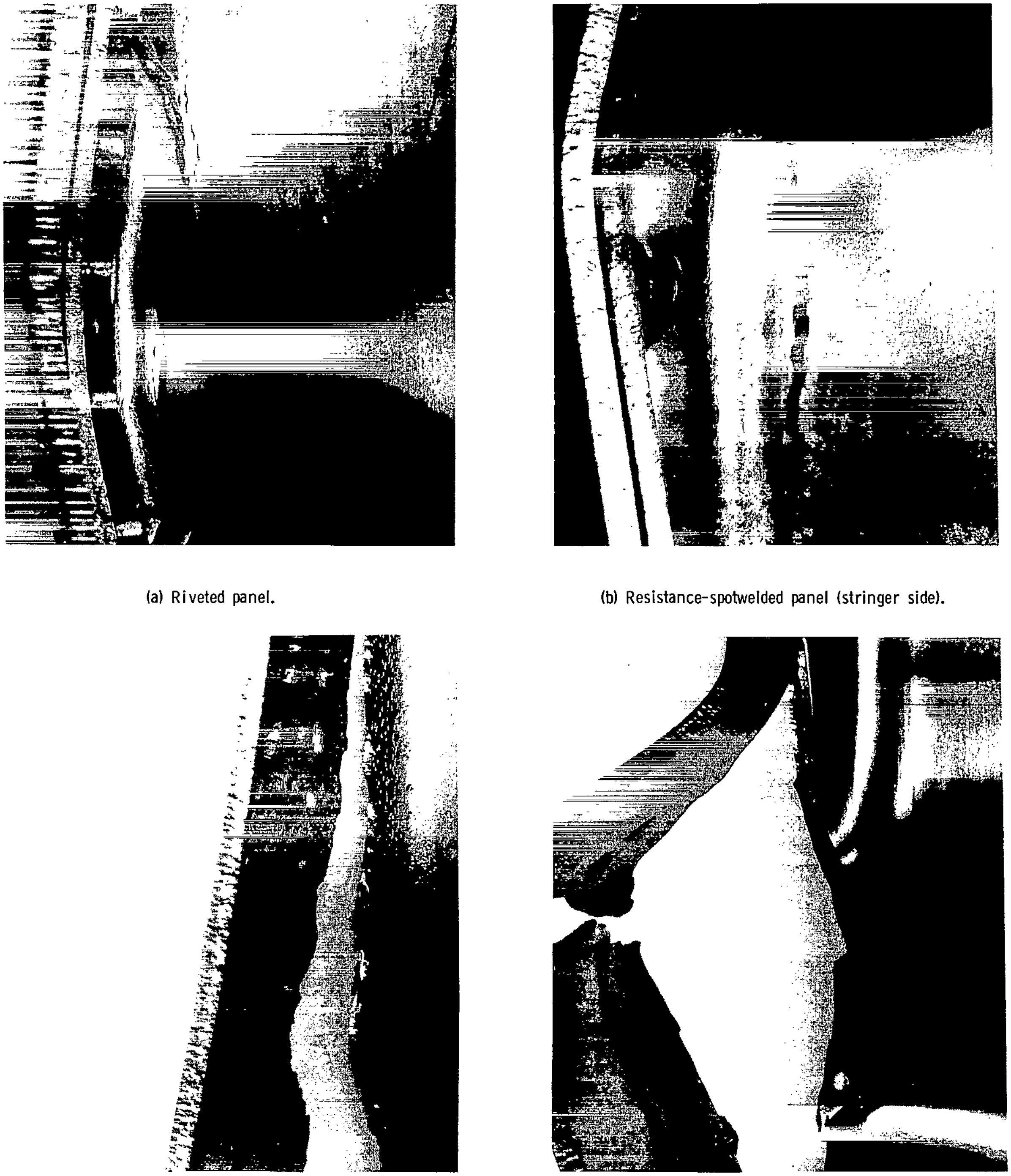


(a) Stringer side.



(b) Skin side. L-69-5138

Figure 6.- Portions of stringers of failed salt-coated panels exhibiting large amounts of tearing. (Arrows indicate the line of sight for fig. 7.)



(a) Riveted panel.

(b) Resistance-spotwelded panel (stringer side).

(c) Resistance-spotwelded panel (skin side).

(d) TIG-welded panel.

L-69-5139

Figure 7.- Hot-salt-stress-corrosion cracking in the bend radii of several panel stringers.

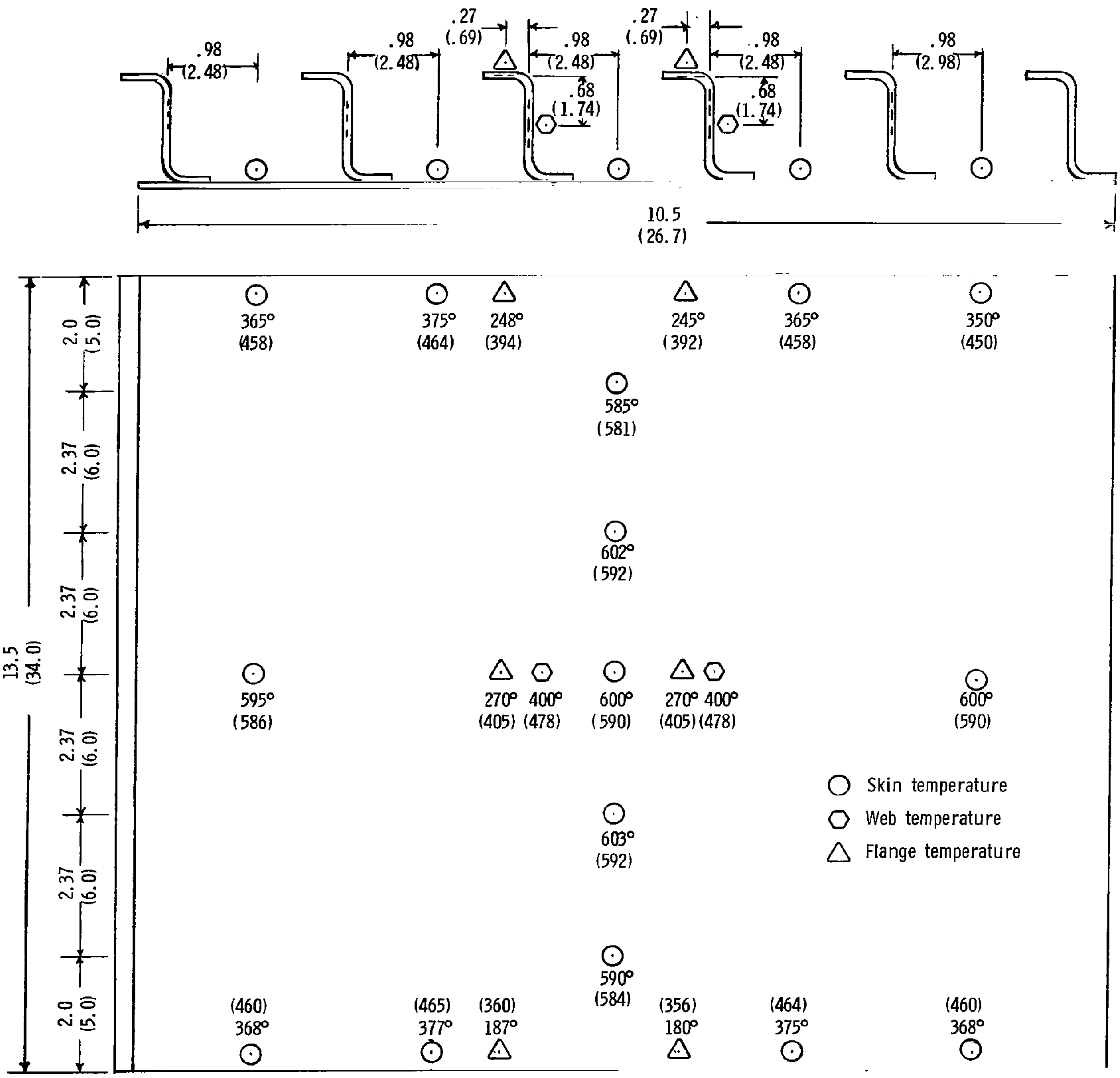


Figure 8.- Typical temperature distribution for a skin-stringer panel tested at elevated temperatures. (Dimensions are shown in inches (cm); temperatures are shown in °F (K).)

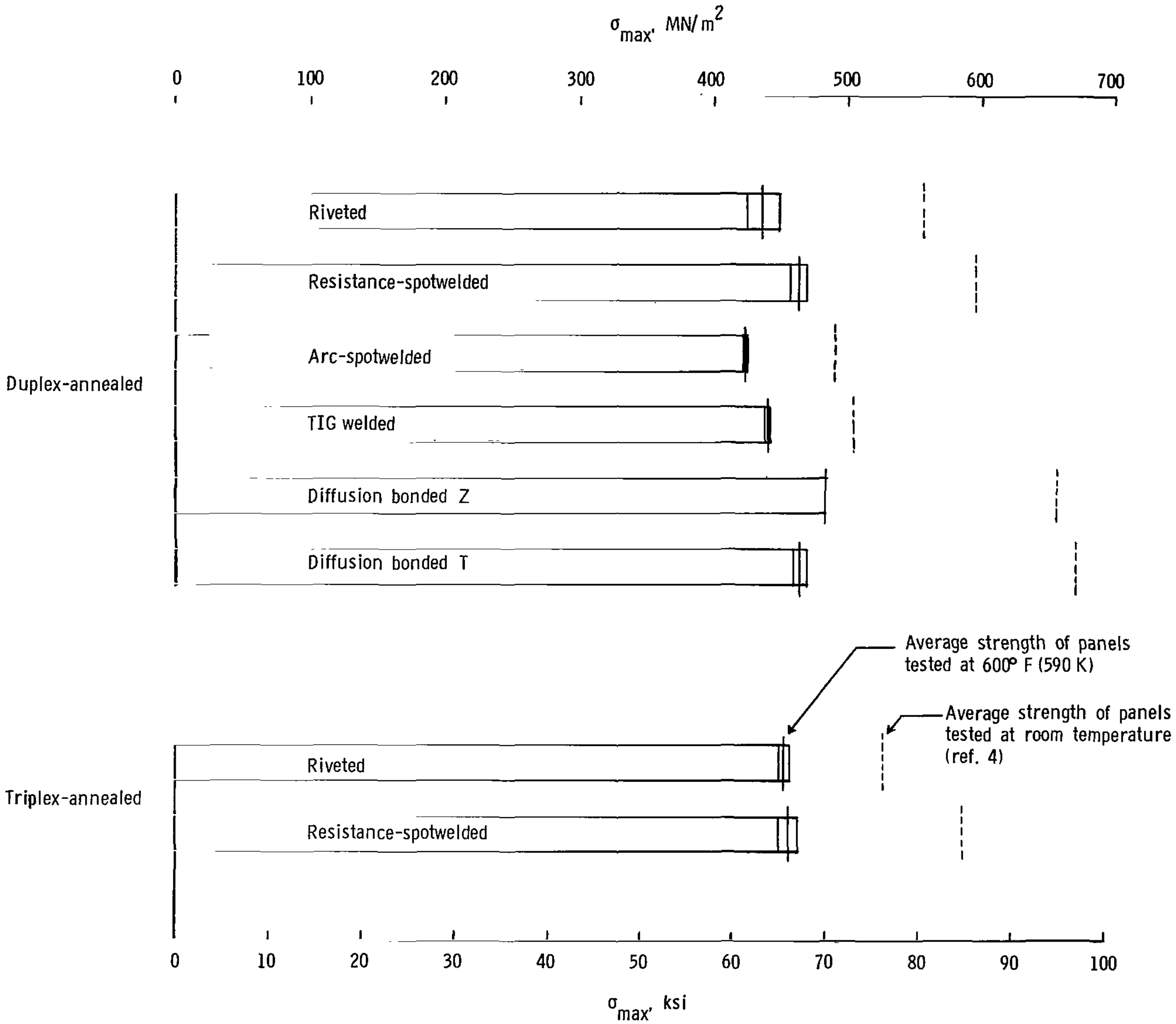
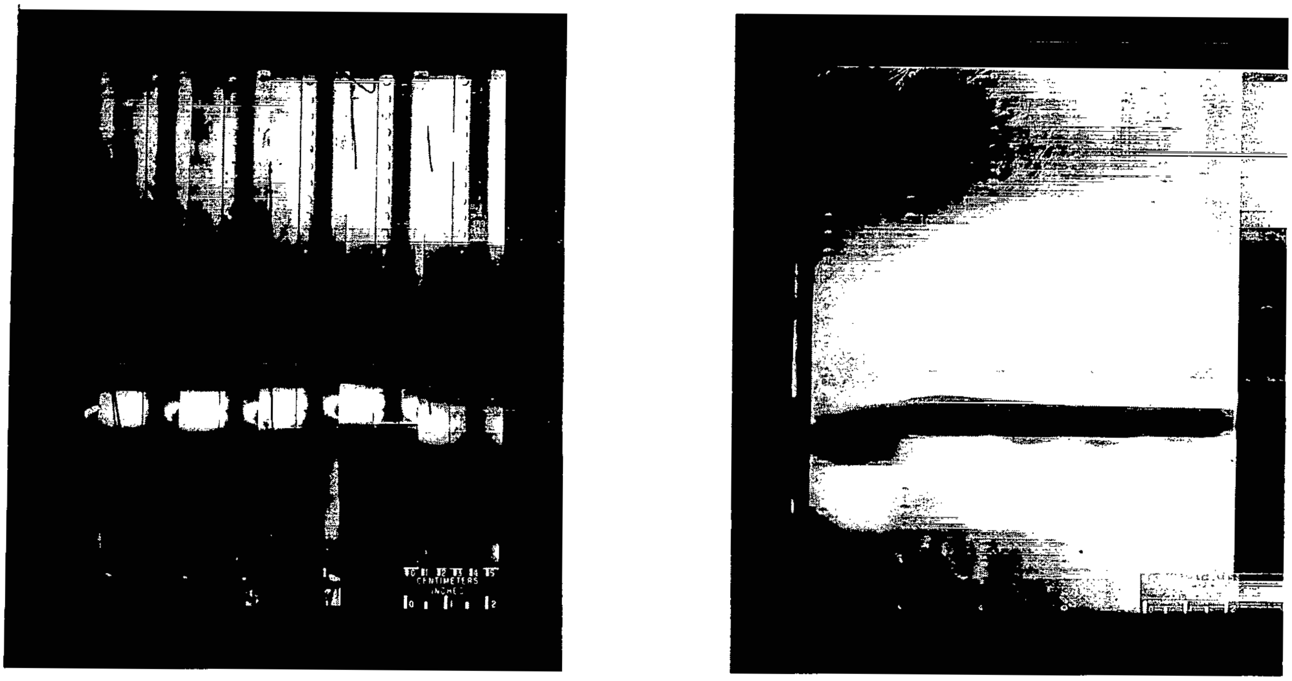
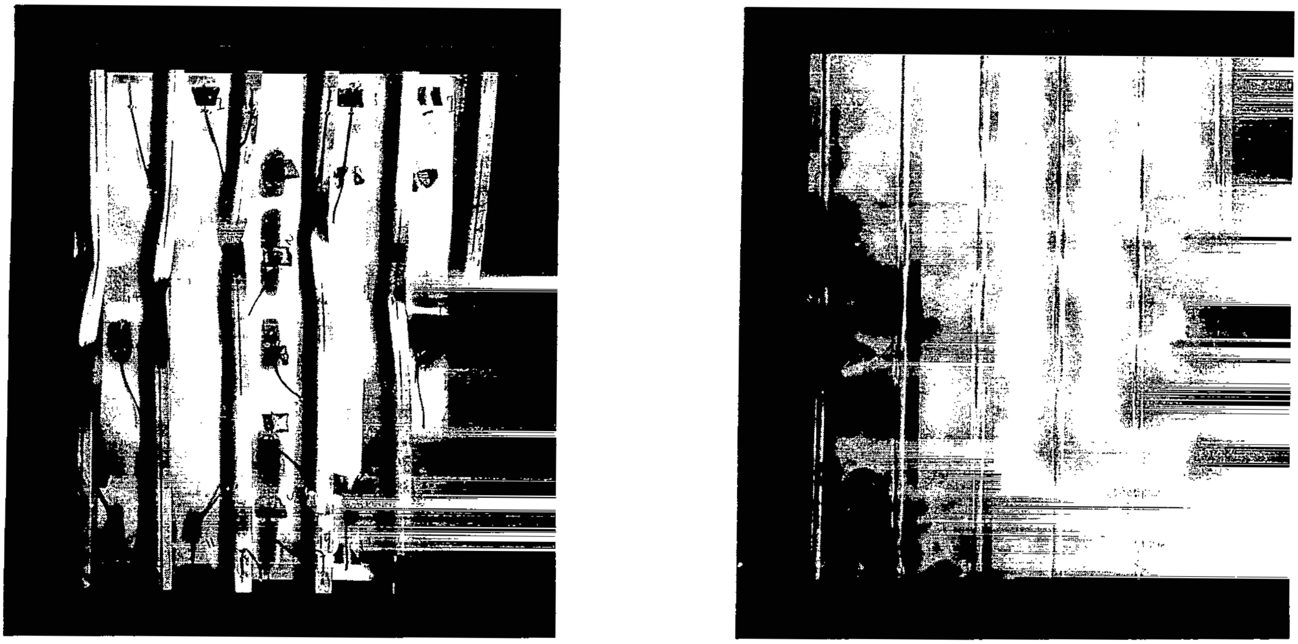


Figure 9.- Comparison of strengths of uncoated panels tested at elevated temperatures with strengths of uncoated panels tested at room temperature in reference 4.



(a) Resistance-spotwelded panel.



(b) TIG-welded panel. L-69-5140

Figure 10.- Typical failures of skin-stringer panels tested at elevated temperatures.

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