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**VERIFICATION TESTS OF DURABLE TPS CONCEPTS**

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## VERIFICATION TESTS OF DURABLE TPS CONCEPTS

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### Abstract

Titanium multiwall, superalloy honeycomb, and Advanced Carbon-Carbon (ACC) multipost Thermal Protection System (TPS) concepts are being developed to provide durable protection for surfaces of future space transportation systems. Verification tests including thermal, vibration, acoustic, water absorption, lightning strike, and aerothermal tests are described. Preliminary results indicate that the three TPS concepts are viable up to a surface temperature in excess of 2300°F.

### Introduction

Although the Reusable Surface Insulation (RSI) tiles currently used on the Space Shuttle are excellent insulators, they are very fragile. Titanium multiwall, superalloy honeycomb, and Advanced Carbon-Carbon (ACC) multipost Thermal Protection System (TPS) concepts are being developed to provide durable thermal protection for surfaces of future space transportation systems which operate at temperatures up to about 2300°F. Figure 1 summarizes the concepts and goals of the development program. The goals of the program are to provide a durable surface of mechanically attached panels with overlapping edges that cover the gaps between panels to reduce gap heating. As shown by the symbols in the graph in the lower right portion of the figure, these concepts are mass competitive with the present RSI TPS, the mass of which is indicated by the cross-hatched area.

This paper reviews verification tests of durable TPS aimed at establishing a preliminary data base from which the designers of future entry vehicles can evaluate the applicability of these TPS concepts to their vehicles. Results are presented from thermal/vacuum, vibration, acoustic, environmental exposure, lightning strike, and wind tunnel tests of the metallic concepts, and thermal/vacuum and arc-tunnel tests of the ACC multipost concept. The test levels are, in general, representative of Space Shuttle design levels which may be more or less severe than levels required for future space transportation systems.

### TPS Concepts

The three TPS concepts identified in figure 1 are also shown in more detail in figures 2 and 3. The two metallic prepackaged concepts (figs. 1 and 2) are discrete panels that have a strip of RTV-covered NOMEX felt beneath the perimeter of each panel to prevent hot gas flow beneath the panels. The titanium multiwall concept (maximum surface temperature < 1200°F) consists of layers of dimpled titanium foil Liquid Interface Diffusion

(LID)\*\* bonded together at the dimples with a flat foil sheet sandwiched between each dimpled sheet. The superalloy honeycomb concept (maximum surface temperature < 2000°F) consists of an Inconel 617 honeycomb outer surface panel, layered fibrous insulation, and a titanium honeycomb inner surface panel. The edges of the two metallic concepts are covered with beaded closures to form discrete panels nominally 12 inches square. The titanium multiwall and superalloy honeycomb panels are described in detail in references 1 and 2, respectively.

The two types of attachments shown in figure 2 can be applied to either of the TPS concepts. The bayonet-clip attachment, shown with the titanium multiwall concept, consists of two clips and a metal tab (bayonet) LID bonded to the lower surface of the panel. One clip is mechanically attached to the vehicle surface, and one clip is LID bonded to the lower surface of an adjacent panel. Thus, a single bayonet attaches a corner from each of two adjacent panels. The through panel fastener, shown with the superalloy honeycomb concept, consists of a thin-walled cylinder through the panel that allows access to a bolt which fastens the panel corner to the vehicle structure. The cylinder, which contains fibrous insulation, is covered with an Inconel 617 threaded plug. These fasteners are described in detail in reference 2.

The Advanced Carbon-Carbon (ACC) multipost concept (maximum surface temperature > 2000°F) shown in figure 3 consists of a rib-stiffened ACC sheet attached to the vehicle primary structure by posts with fibrous insulation packaged in a ceramic cloth between the ACC panel and the vehicle structure. (Venting and waterproofing of the insulation package is a problem area not studied in this investigation.) The surface of the single ACC panel is nominally 36 inches square. The ACC multipost concept is described in detail in reference 3, and fabrication of the ACC test model discussed herein is described in reference 4.

### Verification Test Facilities

NASA test facilities at Johnson Space Center (JSC), Kennedy Space Center (KSC), and Langley Research Center (LaRC) were used for verification tests of the concepts shown in the previous figure. Figure 4 summarizes the types of tests, shows representative test facilities, and identifies the NASA Centers where the tests have been conducted.

TPS test models were exposed to combined temperature and pressure conditions to obtain thermal response characteristics of the concepts using thermal/vacuum test facilities at JSC, KSC, and LaRC. These facilities consist of radiant heaters enclosed in an environmental chamber. One of the facilities, the JSC facility, is shown in

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\*\*Proprietary joining process of Rohr Industries.

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figure 4(a). The heater system, which is suspended over the test model, is mounted in a boiler-plate Apollo-command-module test chamber that is evacuated by a mechanical vacuum pump. The heater consists of electrically heated graphite elements enclosed in a fixture box purged with gaseous nitrogen. One side of the fixture box is a columbium susceptor plate which radiates heat to the test model.

Dynamic response of the metallic concepts was evaluated by shaker-table vibration tests and by acoustic exposure in a sound chamber at JSC and a progressive wave facility at LaRC. The acoustic levels were representative of those experienced during Space Shuttle lift-off. The LaRC facility, shown in figure 4(b), used air modulation to generate the noise which propagates through a horn to the test section. The test panels were attached to the side wall of the test section. (The ACC test model was also exposed to thermal vacuum tests in this facility. Graphite heaters are added to the test section side wall opposite the test panel to provide radiant heating capability.)

Environmental tests to assess water retention and the effects of atmospheric contamination on metallic TPS are being conducted near the Space Shuttle NASA launch site at KSC as shown in figure 4(c). Additional water retention tests are being conducted with a wind/rain machine at JSC.

Lightning strike tests, shown in figure 4(d), were conducted at LaRC to determine how much damage lightning impact caused on the metallic panels. The facility operates by charging a bank of capacitors and rapidly discharging the capacitors to a grounded test model. The maximum capability of the facility is a peak current of 100 kA and an action integral of  $0.25 \times 10^6 \text{ A}^2\text{-sec}$ .

The metallic TPS concepts were tested in the LaRC 8-Foot High Temperature Tunnel (8' HTT) and the ACC concept was tested in the LaRC 20-MW Aerothermal Arc Tunnel to evaluate the performance of the concepts in an aerothermal environment. The upper portion of figure 4(e) shows an array of metallic TPS panels in the 8' HTT, and the lower portion of the figure shows an ACC model in the arc tunnel.

## Results and Discussion

### Thermal Vacuum Tests

Typical results from the thermal vacuum tests of the titanium multiwall, superalloy honeycomb, and ACC panels are presented in figure 5. The metallic panels were tested in the facility shown in figure 4(a); the ACC panel was tested in the facility shown in figure 4(b). The surface temperature histories (lines 1) were imposed during the test, and were used as input to a one-dimensional thermal analysis.<sup>5</sup> Temperatures were calculated at thermocouple locations in the TPS (lines 2) and at aluminum plates (lines 3) which were sized to represent the thermal mass of typical Space Shuttle structure. The surface temperature histories for the titanium and superalloy panels are predicted temperatures at representative points on the Space Shuttle. The measured back surface temperatures on the metallic TPS models indicate acceptable thermal performance

in that they did not exceed 350°F, the maximum allowable temperature. The ACC model was subjected to a surface temperature history similar to that expected for the arc-tunnel tests. (The arc-tunnel can not provide the low heating rates that occur early in the Shuttle entry trajectory.) The calculated temperatures were in good agreement with the measured temperatures.

The condition of the models after several thermal/vacuum cycles is shown in figure 6. The models are undamaged, and the only changes are in appearance. The white surface of titanium multiwall 2-panel array is slightly darkened in areas around the thermocouple wires. This darkening is due to oxidation of the thermocouple sheathing. The white surface on the panels is a titanium-based high temperature coating which has a high solar reflectance and a high emissivity. The darker surface of the superalloy 2-panel array blistered during the first thermal cycle. This surface is a silica-alumina non-catalytic coating which was applied at LaRC after delivery of the test panels. The blistering is attributed to a tool parting material which was not completely cleaned off the surface of the panels after fabrication. (Coupons which were free of this material on the surface before coating survived 80 thermal shocks from room temperature to 2000°F without blistering.) The appearance of the ACC panel after 4500 seconds at 2300°F (fig. 6) is essentially unchanged from its appearance before testing.

### Vibration Tests

Titanium multiwall and superalloy honeycomb panels, each with through-panel attachments, were vibrated on an LaRC shaker table at three different g levels. The results of the tests are summarized in Table 1. The panels with through-panel fasteners were exposed to 10 and 20 g levels of random vibration on each of 3 axes for 600 seconds per level. They were then exposed to 30 g's on each of 3 axes for 485 seconds. This exposure approximates 25 missions. The titanium multiwall panel was not damaged; however, the attachment screws on the superalloy panel became worn from repeated installation and removal. This wear caused the four fasteners to loosen during the last 30-g test and resulted in elongation of the fastener holes, the breaking of two fasteners, and the bending of the other two. These results indicate that new screws should be used on re-installation. Panels with bayonet-clip attachments are scheduled to be tested at JSC.

### Acoustic Tests

Both the titanium multiwall and the superalloy honeycomb concepts were exposed to the acoustic environments listed in figure 7. Two facilities were used, a sound chamber at JSC operating at an overall sound pressure level (OASPL) of 161 dB and a progressive wave facility at LaRC (fig. 2(b)) operating at 159 dB. The spectrums are representative of the sound environment for the Space Shuttle. The 2-panel arrays tested at JSC had bayonet-clip attachments and were exposed to sound for 15 minutes which is representative of about 25 missions with a scatter factor of 4. The single panels tested at LaRC had through-panel fasteners and were tested for 60 minutes which corresponds to about 100 missions with a scatter factor of 4.

In both types of tests, no damage occurred to the titanium multiwall panels. However, the superalloy honeycomb panels did sustain some damage in each type of test. Figure 8(a) shows an edge view of one of the superalloy honeycomb panels tested in the JSC sound chamber. Prior to the test, the overhanging lip along the right half of the panel edge shown was bent down (in a pattern which fits a human hand), and some buckling along the bottom edge of the side closure occurred. Additionally, as pointed out in the figure, this edge was not properly supported by NOMEX felt. All other edges were supported by a 1-inch wide strip of NOMEX felt as specified in the concept design. During the tests, numerous cracks occurred on the bottom edge of this side closure. Since no other side closures on the two panels suffered any damage during the tests, the cracks probably occurred due to the handling damage and lack of felt support on the damaged edge.

One side closure of the single superalloy honeycomb panel tested in the LaRC progressive wave facility was buckled in shipment. The panel was judged to be acceptable for vibration tests since the damage was limited to only one edge. Upon completion of the vibration tests with no visible damage, the panel was exposed to the acoustic load for 60 minutes. After the first 15 minutes, small cracks at the bottom of the buckled side closure were noticed. These cracks were monitored during the remaining exposure, but negligible growth occurred. A typical crack is shown in figure 8(b). Since the only edge to experience these cracks during tests was on the side damaged in shipment, the cracks that developed were probably due to the shipping damage.

Since the titanium multiwall panels showed no damage from the acoustic tests, and the only cracks developed on the superalloy honeycomb panels both at JSC and LaRC occurred in areas which had suffered handling damage prior to the tests, it appears that both concepts will survive sonic environments as high as 161 dB. However, additional acoustic tests may be required to remove the uncertainty.

#### Environmental Exposure Tests

Since thunderstorms occur frequently during the summer months at KSC, and are characterized by heavy rainfall and occasional hail, environmental tests have been designed to determine the water absorption/retention characteristics of multiwall TPS panels under actual rainfall conditions. Figure 9 shows two 1st generation titanium multiwall panels during environmental exposure at Shuttle Launch Complex 39B at KSC. Initial test results have shown that water absorption is not a problem. During a three month exposure period at the launch pad, no water was detected within the titanium multiwall panel. The water detection methods included measuring panel weight gain and using neutron radiography to detect small amounts of water. Additional tests are planned to see if panel orientation affects absorption.

Because KSC is near the Atlantic Ocean, salt and other contaminants can accumulate on the TPS surface over a period of time. Tests are planned to couple launch pad exposure with mission simulations to evaluate long-term environmental effects on metallic TPS. Figure 9 presents an

outline of the general test plan. Current plans are to test titanium multiwall and superalloy honeycomb panels by subjecting them to repeated exposure to contaminants and thermal/vacuum cycles. During the test program, X-ray and other non-destructive techniques will be used to detect any physical changes within the metallic TPS.

#### Lightning Strike Tests

A titanium multiwall panel and a superalloy honeycomb panel were exposed to simulated lightning strikes as shown in figure 4(d). The strike on the titanium multiwall resulted in a conical hole through all the layers of the panel with a hole of approximately 1/8 inch diameter in the lower surface (see fig. 10). However, the damage to the superalloy honeycomb panel (see fig. 10) was limited to the Inconel surface. A spot the size of a dime was indented as though it were hit with a ballpeen hammer. In addition, the face sheet was burned away locally, exposing two of the honeycomb cells. The intensity of these strikes (100 kA) meets the Space Shuttle criteria for lightning strikes on acreage surfaces.<sup>6</sup>

#### Aerothermal Tests

Heating between metallic panels. - A titanium multiwall array and a superalloy honeycomb array were fabricated for radiant and aerothermal tests in the 8' High Temperature Tunnel (HTT) at LaRC. These arrays, shown in figure 11, consisted of 20 panels and were configured to fit a standard panel holder used in the 8' HTT. The panel holder has an opening, 60 in. x 42.5 in., and can accept test-specimen thicknesses up to about 12 inches. Since the standard metallic TPS panel is 12 inches square and the panel holder is 42.5 inches wide, panels approximately 6 inches wide were used to close out the array.

Figure 12 shows the titanium multiwall TPS 20-panel array mounted in the panel holder and installed in the 8' HTT. The view is taken looking downstream in the tunnel. Fences attached to each side of the panel holder provide relatively uniform two-dimensional flow on the surface of the panel holder. As can be seen on the model, the panels were installed such that two of their edges were parallel to the flow direction. This installation is considered a "worst case" orientation of the panels with respect to the flow.

The insert in figure 12 shows a schematic view of the major components of the 8' HTT which is a "blow-down" tunnel. The model is held in a pod beneath the test section and covered by radiant heaters which not only preheat the model but also protect the model from tunnel start-up and shut-down loads. After the model is preheated and the tunnel is started, the radiant heaters are turned off and retracted by hydraulic actuators. The model is then rapidly inserted into the 8-foot diameter test stream by a hydraulically-operated 15-ton elevator which raises the model to the test position in approximately 1 second. For shutdown, the procedure is reversed. The total aerothermal test duration is up to two minutes depending on test conditions.

One of the objectives of the aerothermal tests was to determine if temperatures in the gaps between panels would be increased by exposure to

the flow. Such an increase would indicate that the panel edge overlap which covers the gap is not adequate by itself to prevent gap heating when the flow is parallel to the gap. Tests of an array of 1st generation titanium multiwall panels indicated that flow did not occur in the gaps when the panels were oriented 30° to the flow.<sup>7</sup>

Surface temperatures and temperatures at the bottom of the gap are shown in figure 13 for both the titanium multiwall array and the superalloy honeycomb array. The dashed curves show temperatures during a 200 second portion of an aerothermal test when the array was inserted into the tunnel stream. The solid curves show temperatures recorded at the same locations and time intervals during a static radiant heating test. At the time interval shown, the surface and gap temperatures of the titanium multiwall model were at equilibrium. When the model was inserted into the flow, negligible temperature perturbation occurred at the bottom of the gap thus indicating no additional gap heating occurred. Although the surface of the superalloy honeycomb panel reached equilibrium, the temperature at the bottom of the gap, was still approaching equilibrium when the radiant heaters were turned off and the model was inserted into the flow. Immediately after the superalloy model was inserted into the flow, the temperature at the bottom of the gap increased to a level considerably greater than it was before the tunnel started. This high, quick temperature rise indicates that hot gases flow in the gaps between panels. Thus, when the edges of the superalloy panels are parallel to the flow, the overlapping edges do not provide an adequate seal. Superalloy honeycomb panels may be more susceptible to gap heating because the gap is much larger than the gap between titanium multiwall panels. Consequently, when thermal expansion closes the top of the gap, the bottom of the gap remains partly open because it is much cooler.

#### Surface heating of damaged metallic panels. -

During the first test of the titanium multiwall 20-panel array, failure of the control thermocouple feedback allowed the radiant preheaters to quickly heat the surface of the array to a temperature in excess of 1700°F for a period of about 12 seconds. The rapid rise to such a high temperature (maximum design temperature is 1200°F) caused slight scorching and buckling of the upper surface of the panels and also resulted in debonding of the upper skin over an area of 5 in.<sup>2</sup> to 10 in.<sup>2</sup> on each of two panels. The array subsequently withstood five aerothermal tests without additional damage.

The original test plan for the 20 panel arrays included aerothermal tests with the lightning damaged panel included in the array. The lightning-damaged titanium multiwall panel was unchanged by the aerothermal test. Furthermore, a negligible increase in temperature (less than 10°F) occurred on the backside of the panel at the area of damage. Thus, lightning damage of the titanium multiwall concept does not appear to be a design concern.

The lightning-damaged superalloy honeycomb panel could not be installed into the array in a timely manner; therefore, panels already in the array were damaged to simulate the lightning damage. Figure 14 shows the types of damage inflicted on the panels. The two rows of panels in

the foreground of figure 14, which were coated with a ceramic non-catalytic coating,<sup>8</sup> were the panels that received the damage. (The dark panels in the background were coated with a high temperature, high emittance paint.) Figure 15 was made from a frame of movie film taken during this last aerothermal test of the superalloy honeycomb 20-panel array in the 8' HTT. The only light used to expose the film was that radiating from the model which was at a temperature of about 1850°F. The thermal deflections of the heated model resulted in panel "pillowing" which causes slightly higher temperatures to occur on the upstream side than on the downstream side of the individual panels.<sup>9</sup> The greater brightness (and higher temperature) of the right-hand side of the array (looking downstream) is caused by the lower emittance of the panels with the non-catalytic coating.

Several hot spots can be seen where the face sheet buckled and delaminated from the honeycomb core. This damage occurred early in the test program when fiberglass curtains, used to protect surrounding structure from radiation from the quartz heaters, melted and fell on the panels. The buckles and delaminations did not propagate during the balance of the test program. A hot spot was caused by the torch burn-through, shown on figure 14. The other two damaged locations and the open attachment hole did not appear to cause any significant overheating. Bent up gap covers also showed up as hot spots since they protrude into the air flow. The gap covers in the rear of the model were in contact with the rigid glassrock which surrounded the array and were deformed when the panels bowed thermally. The gap-cover hot-spot that occurred at the intersection of four panels was probably caused by thermal bowing interference between panels with different attachments. This was the only intersection where a bayonet-clip-attached panel overhung a panel with through-panel attachments.

Post-test inspection of the array was not possible because, at the end of this test, part of the panel holder broke loose and caused the tunnel to "unstart." The strong shock wave (10 psi pressure rise in about 0.2 seconds) passing through the test section completely destroyed the array of panels.

#### Non-catalytic coating for metallic panels. -

For the same entry conditions, a metallic surface of an entry vehicle will be subjected to a higher heating rate than a non-metallic surface. This difference occurs because oxides of high temperature structural metals are generally catalytic to the recombination of dissociated air molecules, and the energy of dissociation released during recombination adds to the heat load.<sup>10</sup> A non-catalytic coating will reduce the heat load to the surface and greatly increase the thermal efficiency of metallic TPS.

A commercially available, water base, silica-alumina ceramic coating was evaluated by exposing coated and uncoated Inconel 617 specimens in the LaRC 1 MW Aerothermal Arc Tunnel using air as a test stream. Prior to the arc tunnel tests, the emittances of specimens were measured, and coated specimens were subjected to 80 thermal shock cycles in a 2000°F furnace to evaluate the adhesion of the coating to the metal.<sup>8</sup> The measured

emittance of the coated and uncoated (but oxidized) specimens were 0.65 and 0.8, respectively. The coating remained attached during the thermal shock cycles, and the emittance did not change.

The results of the arc-tunnel tests are shown in figure 16. Arc-tunnel test conditions were established which resulted in a temperature of 1753°F on the uncoated specimen. The coated specimen was tested at the same condition, but reached only 1353°F. Modification of the coating composition to increase surface emittance without harming the non-catalytic and adherence characteristics would further reduce the temperature. Radiation equilibrium heating rates were calculated using the maximum measured surface temperatures and the measured emittances. The heating rate on the coated specimen was only 37 percent of the heating rate on the uncoated specimen.

This coating was applied to several superalloy/honeycomb TPS test panels exposed to wind tunnel, thermal/vacuum, lightning strike, vibrational and acoustic tests. Results from these tests further indicate that the non-catalytic coating adheres well. Thus, an adhering, non-catalytic coating is feasible and should be used for metallic TPS; however, emittance greater than 0.65 is desirable.

Curved metallic panels. - Even though much of the surface of Shuttle-type vehicles is flat or nearly flat, some locations, such as the chine areas, are necessarily curved. The fabrication of curved TPS panels often presents complexities not encountered in fabricating flat panels, and the design of curved panels must include large surface pressure gradients and factors contributing to thermal stress which are normally not important in the design of flat TPS.

A curved titanium multiwall panel has been fabricated to demonstrate that the multiwall concept will lend itself to curved panels,<sup>11</sup> and an array of curved superalloy panels has been fabricated for aerothermal tests to evaluate their performance in a high-surface-pressure gradient environment. The curved 20-panel array shown in figure 17 will be installed into the cavity of the Curved Surface Test Apparatus (CSTA), so that the surface of the array will be flush with the surface of the CSTA. The array will be instrumented with thermocouples and pressure sensors and tested in the LaRC 8' HTT to determine if heating occurs in the gaps between panels. Metal tabs, one of which is identified on the single panel in figure 17 are located at the corner intersections of the panels to block flow in the gaps. All of the panels are attached with through-panel fasteners.

One of the main differences between the design of flat and curved TPS is the effect of curvature on thermal stress. The thermal stresses in an unconstrained structure are zero if the temperature distributions through the structure are linear when they are measured in a rectangular Cartesian coordinate system.<sup>12</sup> The flat panel shown in figure 18 has a linear temperature distribution through the depth, and since this distribution results in a linear (constant in this instance) temperature distribution in the  $z = \text{constant}$  plane, no thermal stress occurs. However, the same linear temperature distribution through the depth of the

curved panel shown in figure 18 results in a nonlinear temperature distribution in the  $z = \text{constant}$  plane. Consequently, thermal stresses occur in the curved panel even if the temperature distribution through the depth is assumed to be linear.

Linear, elastic stress analyses of the curved superalloy panel using the SPAR finite element structural analysis computer program<sup>13</sup> and using temperatures calculated from a one-dimensional thermal analysis have shown that the thermal stresses increase as the size of the panels increase.<sup>14</sup> Furthermore, results have shown that a change in length has a greater effect on thermal stresses than a change in width (width being measured in the direction of curvature). Panels 6 inches in length were found to have acceptable stresses (less than yield stress), but panels 12 inches in length were found to have stresses nearly 2.5 times greater than yield. However, even for the 12 inch panel, the strain calculated from the linear elastic analysis was slightly less than yield. Since thermal stress is induced by an applied strain (as opposed to an applied force), the stress calculated from a nonlinear analysis would be expected also to be slightly less than yield. Even though this stress would be high, the fatigue life calculated by the method of universal slopes and the "10 percent rule"<sup>15</sup> is approximately 1800 cycles which is more than adequate for space transportation vehicles that experience only 1 thermal cycle per mission.

Thus, two methods exist to control thermal stress in curved panels (1) to reduce size, and (2) to allow some plastic deformation to occur on the first cycle after which the remaining cycle life may be adequate. Consequently the array of curved panels contains both 6-inch and 12-inch long panels (fig. 17) so that the performance of both sizes can be evaluated. Additionally, a single 12-inch long panel separate from the array will be heavily instrumented with strain gages and thermocouples and tested under radiant lamps to measure thermal stresses which will then be compared with analytical results.

ACC multipost. - The same 1 ft. by 2 ft. test model, figure 19, that was subjected to the thermal vacuum tests was also subjected to aerothermal tests. The model is shown in figure 20 installed in the LaRC 20-MW Aerothermal Arc Tunnel. The model was mounted in a water-cooled holder at 15° angle of attack to the stream with a 6-inch transition section between the nozzle and the model. Conditions were selected which gave a 2300°F surface temperature on the front of the model. Figure 2(e) shows the model in the test stream. Only light being radiated from the model was used to expose the film.

A comparison of temperatures obtained during the arc-tunnel tests with those obtained during a thermal/vacuum test is shown in figure 21. The temperature was measured at the center of the model where pieces of 4 separate panels intersect. Thermocouples placed at locations 1, 2, and 3 measured the temperature at the ACC skin, at 1/3 of the depth of the model, and at the bottom of the model, respectively. The tunnel condition resulted in a surface temperature (1) nearly 100°F less than that obtained during the thermal/vacuum test. However, the temperature measured at 2 during the

arc-tunnel test was not less than that obtained during the thermal vacuum test, indicating that slight heating due to flow occurred in the gap region where one panel overlaps another. A local design change may be required if this preliminary conclusion is sustained by additional test results and if the heating is found to be significant. The lower temperature measured on the aluminum plate during the tunnel test was encountered at other locations and probably reflects a larger heat-sink effect caused by a water-cooled holder which was not used in the thermal/vacuum tests.

The ACC model was not damaged by either the thermal/vacuum or arc-tunnel tests. The appearance of the model before and after tests is shown in figure 22. The only change in appearance occurred during the arc-tunnel tests when erosion of copper electrodes caused an orange-colored copper deposit on part of the model surface.

#### Concluding Remarks

The results from a variety of verification tests indicate that the three TPS concepts (titanium multiwall, superalloy honeycomb, and ACC multipost) are viable over a temperature range from 700°F to a temperature greater than 2300°F.

The metallic TPS appears suitable for acoustic environments up to 161 dB although results for the superalloy honeycomb are not conclusive because small cracks developed in areas which had suffered handling damage prior to the tests. Based on environmental tests of titanium multiwall panels, the metallic TPS are not susceptible to water ingress. Both the titanium multiwall and superalloy honeycomb TPS suffered only minimal damage from lightning strikes, and there was no progressive damage during subsequent limited aerothermal tests. The thermal performance of the metallic TPS was essentially as predicted although there was evidence of hot gas ingress and heating in the covered gaps of the SA/HC array (the tiles were installed with the gaps parallel to the flow--a worst case orientation). To overcome this problem, flow blockers have been incorporated in the design of an array of curved panels which will be tested in an aerothermal environment to assess their effectiveness in a flow field with large pressure gradients.

Supplemental tests of a non-catalytic coating indicated that a non-catalytic surface can significantly reduce the heating to metallic surfaces. Tests indicate that the coating adheres well, however modification to increase the emissivity is desirable.

The ACC multipost concept survived repeated thermal exposures to 2300°F with no evidence of degradation. The thermal performance was as predicted, however preliminary aerothermal test results indicate slightly higher local heating occurs at the joints between panels. A local design change may be required if this conclusion is accurate and if the heating is found to be significant.

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Table 1 Vibration tests on M/W and SA/HC panels  
(Shaker Table)

Concept	Attachment	Facility	Exposure		Comments
			Level	Time	
Ti M/W	Through-Panel	LaRC	10, 20 g's 3-axes	600 sec per level	Approximates 25 missions; no damage
			30 g's 3-axes	485 sec per level	
	Bayonet-Clip	JSC	TBD	TBD	Test pending
SA/HC	Through-Panel	LaRC	10, 20 g's 3-axes	600 sec per level	Approximates 25 missions; attachment screws worn from repeated disassembly
			30 g's 3-axes	485 sec per level	
	Bayonet-Clip	JSC	TBD	TBD	Test pending

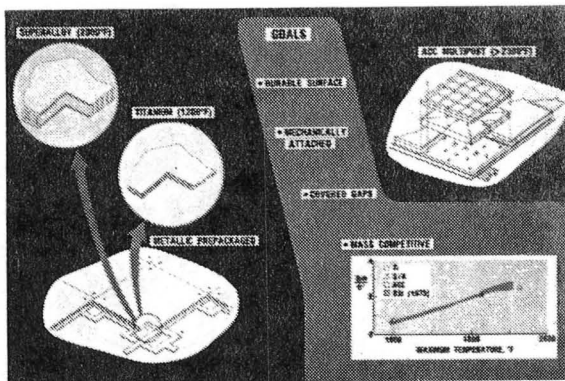


Fig. 1 Durable TPS concepts.

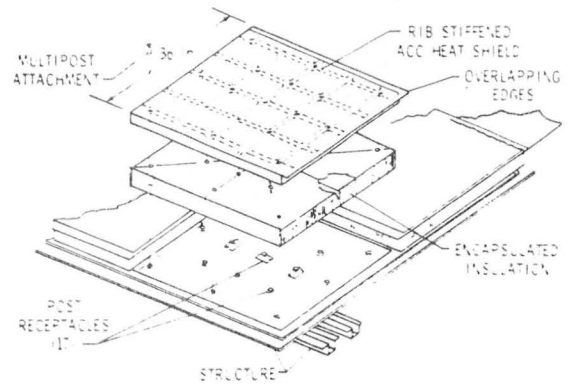


Fig. 3 Advanced carbon-carbon multipost standoff TPS concept.

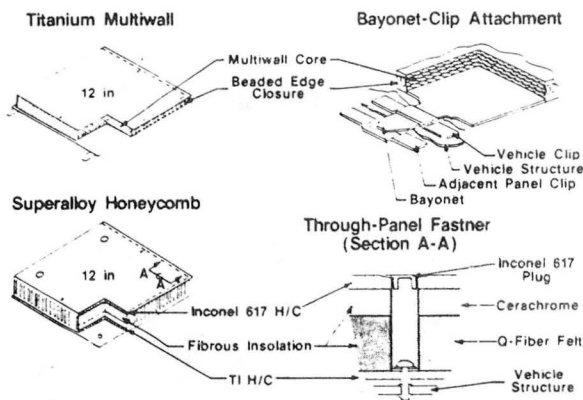


Fig. 2 Metallic TPS concepts.

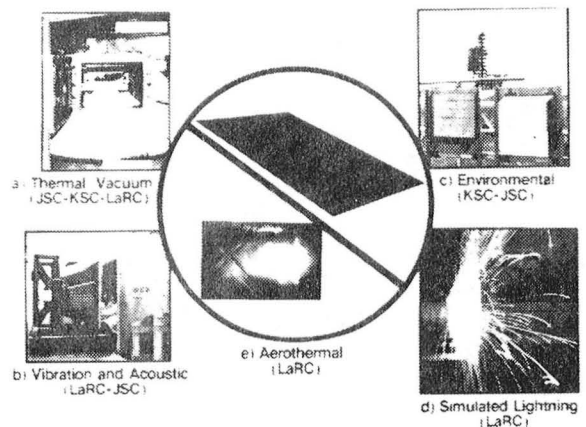


Fig. 4 Verification test facilities.

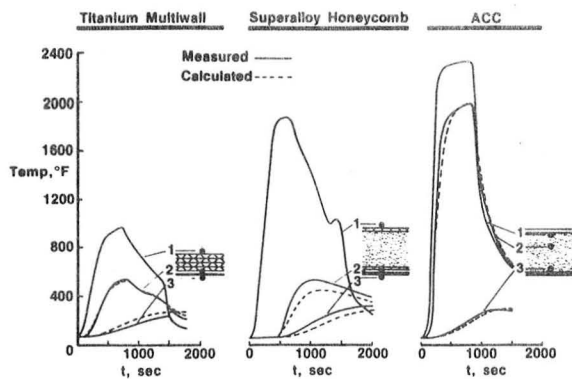


Fig. 5 Thermal/vacuum tests.

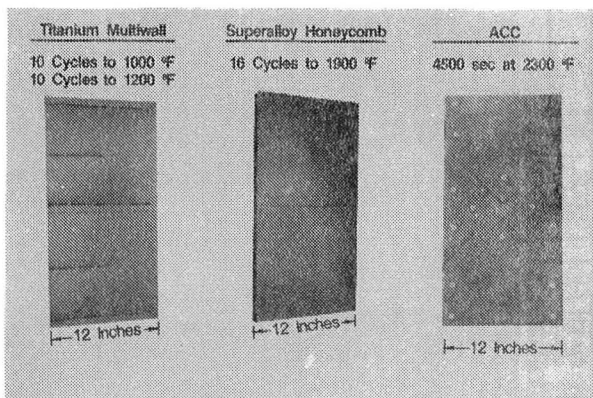


Fig. 6 TPS models after thermal/vacuum tests.

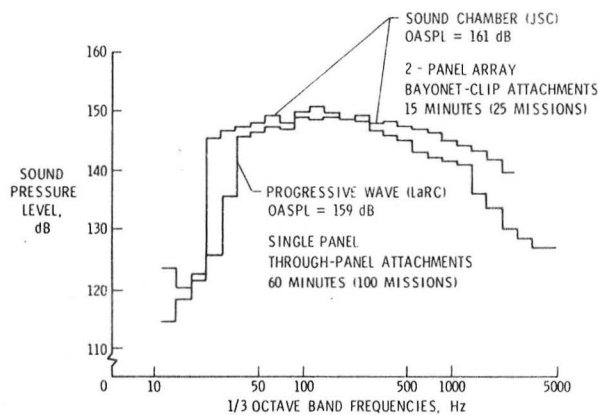


Fig. 7 Acoustic tests on M/W and SA/HC panels.

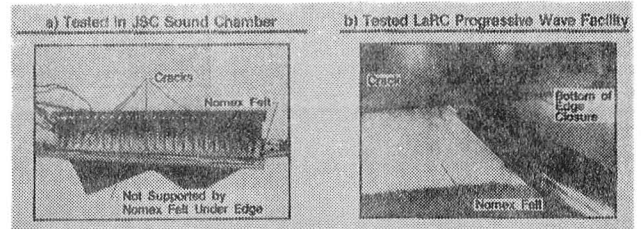


Fig. 8 Damage from acoustic tests of superalloy honeycomb.

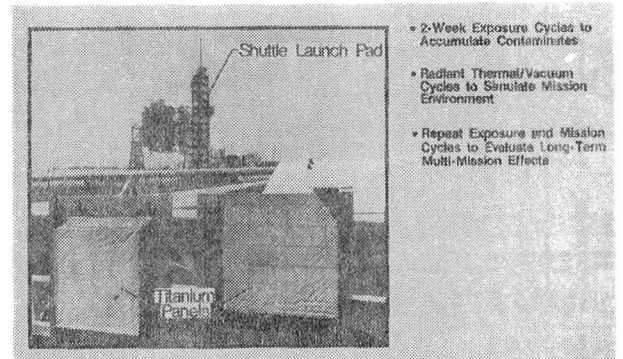


Fig. 9 Environmental exposure of metallic panels at KSC.

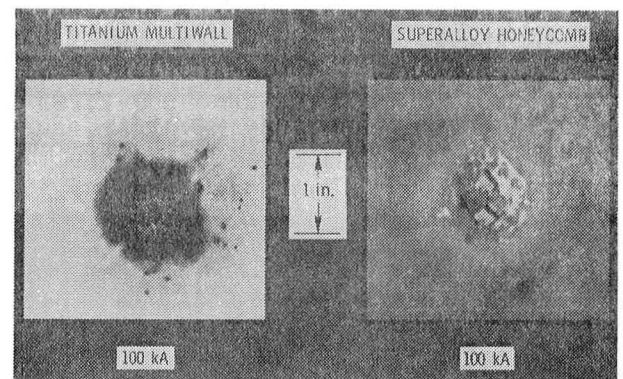


Fig. 10 Simulated lightning strikes on metallic TPS.

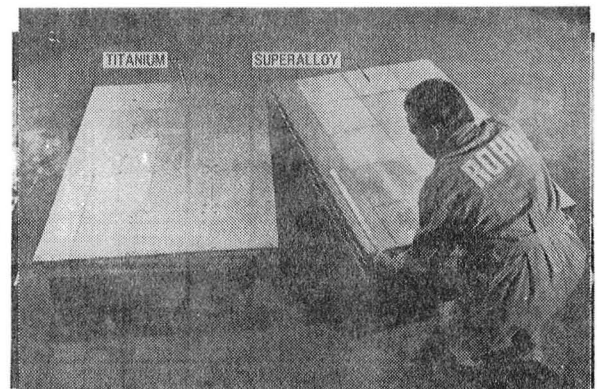


Fig. 11 Metallic TPS arrays for 8-Foot High Temperature Tunnel tests.

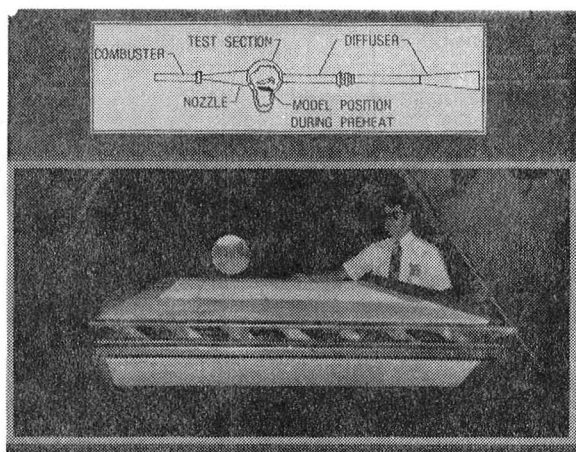


Fig. 12 Titanium multiwall 20-panel array in LaRC 8-Foot High Temperature Tunnel.

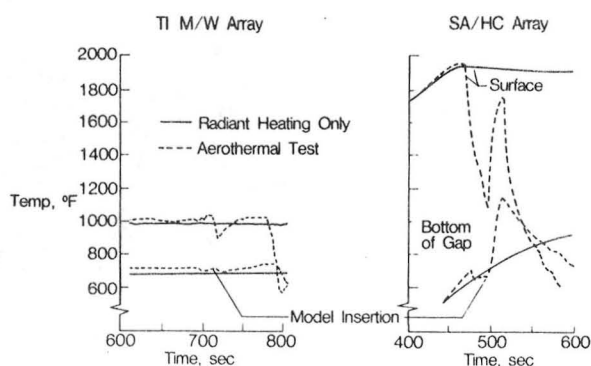


Fig. 13 Effect of aerothermal exposure on gap temperature.

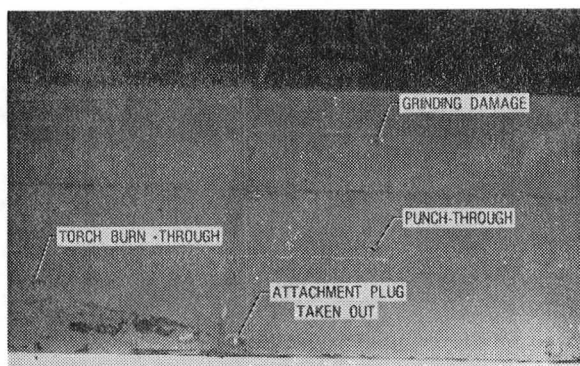


Fig. 14 Intentional surface damage to SA/HC 20-panel array.

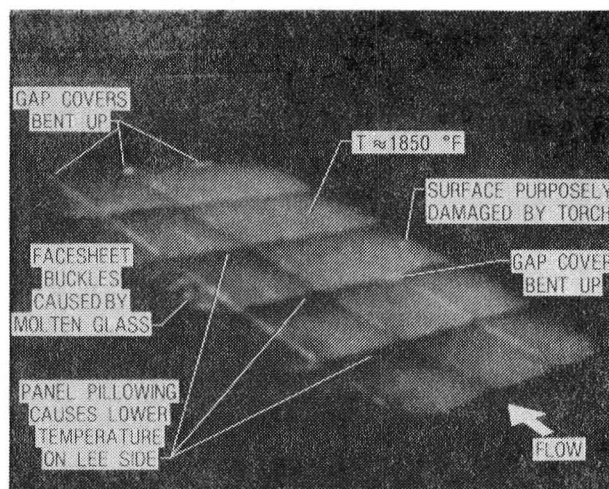


Fig. 15 SA/HC 20-panel array in 8-Foot High Temperature Tunnel.

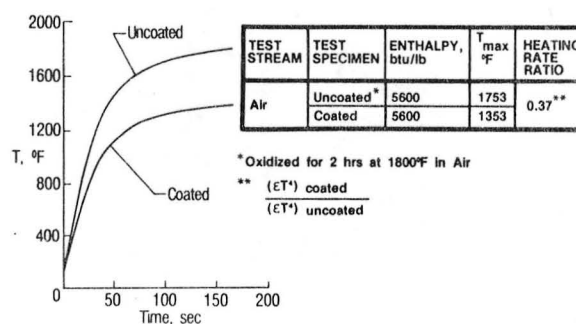


Fig. 16 Non-catalytic coating arc-tunnel test results.

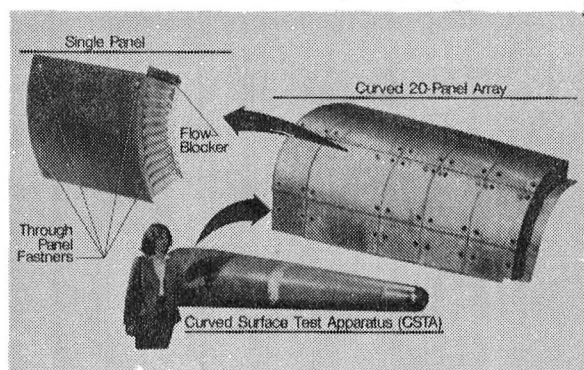


Fig. 17 Curved superalloy honeycomb TPS panels.

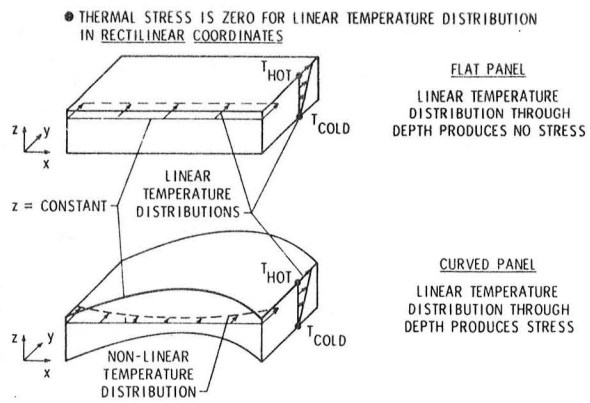


Fig. 18 Effect of curvature on thermal stress of unconstrained panel.



Fig. 19 ACC multipost TPS test article.



Fig. 20 ACC multipost TPS in arc-tunnel.

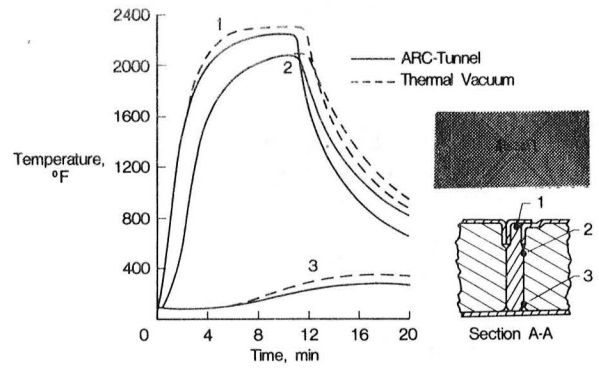


Fig. 21 Effect of aerothermal exposure on gap temperature - ACC multipost.

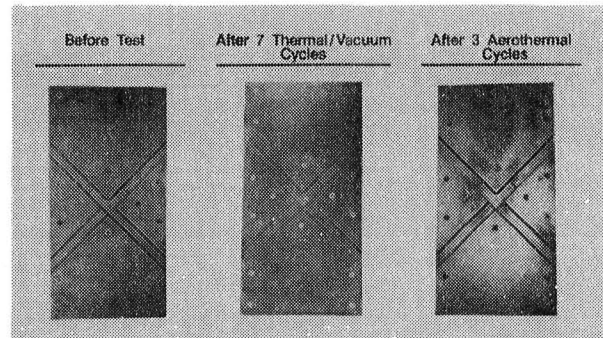


Fig. 22 ACC multipost test model.



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16. Abstract  Titanium multiwall, superalloy honeycomb, Advanced Carbon-Carbon (ACC) multipost Thermal Protection System (TPS) concepts are being developed to provide durable protection for surfaces of future space transportation systems. Verification tests including thermal, vibration, acoustic, water absorption, lightning strike, and aerothermal tests are described. Preliminary results indicate that the three TPS concepts are viable up to a surface temperature in excess of 2300°F.					
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