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Strength Integrity of the Space Shuttle Orbiter Tiles

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STRENGTH INTEGRITY OF THE SPACE SHUTTLE ORBITER TILES

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Abstract

The Thermal Protection System (TPS) of the Space Shuttle Orbiter is a unique, specially developed system for thermally protecting the conventional aluminum structure from the intense heat encountered during reentry to the earth's atmosphere. Three material systems comprise the total TPS, but the one of pure-silica fiber tiles, covering most of the vehicle, is dealt with in this paper. The tiles, which are extremely lightweight, brittle, and low strength must maintain their structural integrity through the grueling acoustic and aerodynamic load environments of Shuttle launch, the thermal extremes of space operation, and the high temperatures of reentry. To assure that each of the more than 30,000 individual tiles had adequate strength, it was necessary to define and verify the macroscopic vehicle loads and environments and then the microscopic tile loads and environments; to stress analyze each tile for its unique configuration and environment; to demonstrate the integrity of selected tiles by acoustic, aerodynamic, thermal, vibration, static load, and combined environment tests; and then to proof load the tiles after installation on the Orbiter. It was necessary to develop, late in the program, processes for doubling the strength capability of the bonded interface of the tiles, pulling on the fragile tiles bonded to the Orbiter and yet making sure that this loading did not result in excessive damage to the tile, and nondestructively determining the strength of the silica material. The highly successful maiden flight of the Orbiter Columbia was a testimony of the Thermal Protection System's strength integrity.

I. Introduction

The maiden flight of the Space Shuttle during April 12-14, 1981, was very successful and marked the beginning of an era of reusable spacecraft. A major element of the Orbiter spacecraft which allows it to be reusable is its thermal protection tiles. Of the problems encountered in the development of this spacecraft, none were more challenging to solve than the structural integrity design and verification of the more than 30,000 tiles. The tiles which this article addresses are one of the three major material systems which comprise the total Orbiter TPS and which had to meet the general design requirements:

- o Limit structure temperature to 350° F
- o Useful life of 100 missions
- o Withstand surface temperatures from $-250°$ F to $2500°$ F
  Heat loads to 60,000 Btu/ft^2
  Acoustic levels to 166 dB
  Aerodynamic pressure (freestream) to 819 psf
- o Provide the aerodynamic moldline
- o Attach to aluminum structure
- o Economical weight and cost

II. System Description

The area of the vehicle protected by the tiles is shown in Fig. 1 and designated as reusable surface insulation (RSI). As can be seen in Fig. 2, the tiles protect the vehicle from surface temperatures in the range of 700° F to 2300° F. The highest temperature regimes (up to 2800° F), which are also the leading edges of the wings and the fuselage nose, are hot structures produced

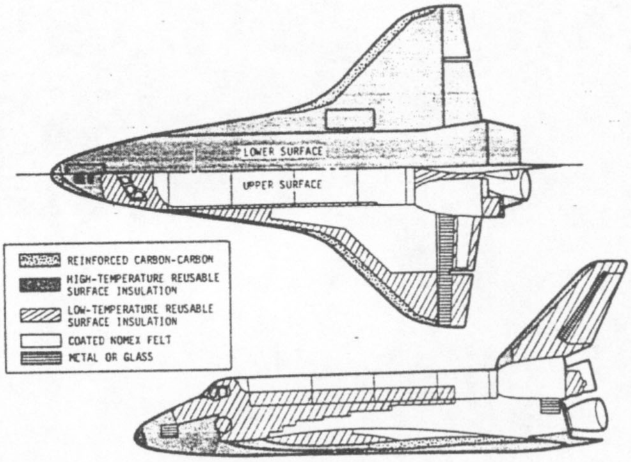

Fig. 1 Thermal Protection System.

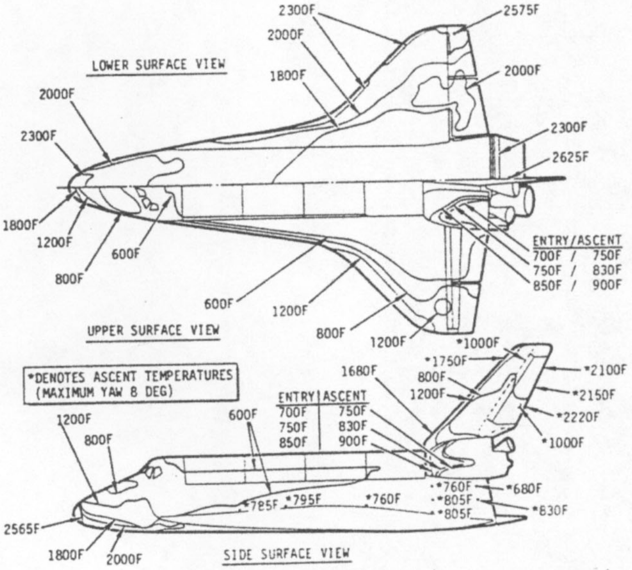

Fig. 2 Orbiter isotherms: trajectory 14414.1C.

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from carbon-carbon material layed-up on tooling, like fiberglass. Regions of the vehicle below 1000° F are thermally protected by large blankets of Nomex felt coated with room temperature vulcanized (RTV) rubber - designated as flexible reusable surface insulation (FRSI).

The RSI tiles, shown conceptually in Fig. 3, are designed to radiate 90% of the reentry heat back to space before it can be conducted to the Orbiter's structure. Since the structure deforms in-plane during a mission, continuous covering for large areas would not work without fracturing the structurally weak silica material - thus, the nominal 6-inch square tile with a 0.05-inch gap between it and its neighbor. To accommodate the flight-induced out-of-plane structural deformation, the individual tiles are mounted on a compliant strain isolation pad (SIP) made of the same material as FRSI, Nomex felt. The design concept of individual tiles on SIP becomes fairly obvious with a limited amount of stress analysis using the RSI physical properties shown below.

Properties of Reusable Surface Insulation

	Low density	High density
Material:	High-purity silica fiber, LI-900	Same, LI-2200
Density:	9 lb/ft^3	22 lb/ft^3
Strength		
NORMAL Thermal tension	13 psi	35 psi
In-plane tension	41 psi	100 psi
Modulus of elasticity	6000 psi	36,000 psi
Thermal coefficient of expansion	2.7×10^{-7} in./in./°F	2.7×10^{-7} in./in./°F

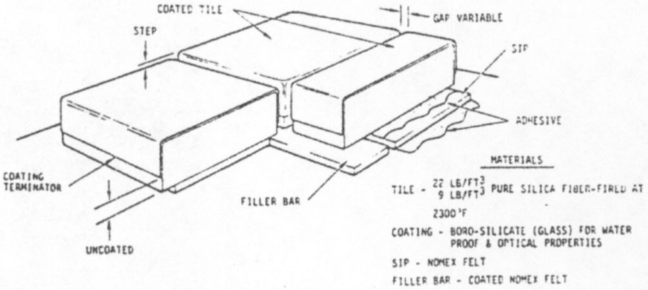

Fig. 3 Tile design.

As the LI-900 RSI 13-psi ultimate strength allowable was being established, the strength properties of the tile/SIP system were also being established. The effective joint allowable of this interface was approximately 50% of that of the LI-900 material. This lower strength allowable was caused by stress concentrations in the RSI because of "stiff spots" in the SIP. The challenge of accommodating these "stiff spots" for the more highly loaded tiles, and not simply using the heavier, higher strength LI-2200, was met by locally densifying the tile/SIP interface.

Densification is a very simple process and yet very effective for locally enhancing the strength of the tile. A solution of colloidal silica particles is applied with a brush to the noncoated surface of the tile and baked in an oven at 350° F for 3 hours. The densified layer is approximately 0.1 inch thick and increases the weight of a typical 6-inch by 6-inch tile by approximately 0.06 pound. For load distribution, the densified layer serves as a plate which distributes the concentrated SIP loads into more evenly distributed loads when they reach the unmodified silica fibers. As shown in Fig. 4, this forces the failure surface above the densified layer. This enhancement in itself offers somewhat of a fail-safe feature for thermal protection, but the major enhancement is in the improved tile/SIP system strength shown in Fig. 5.

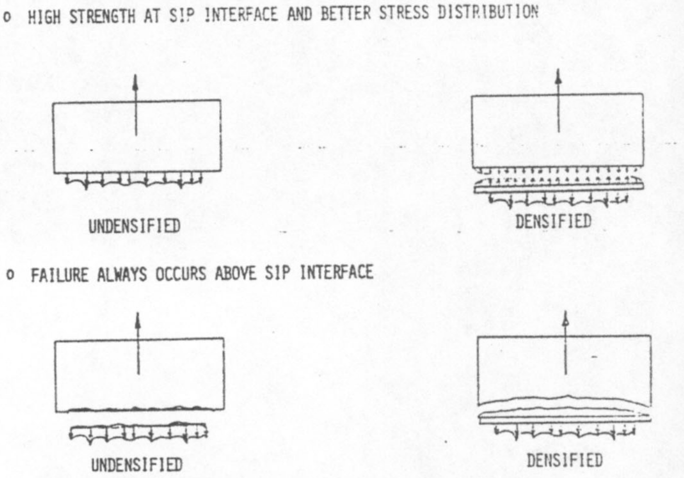

Fig. 4 Salient features of densified tiles.

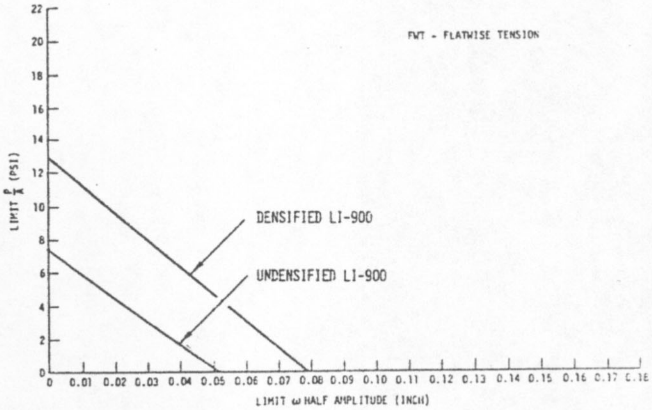

Fig. 5 Allowable FWT in presence of substrate deflection.

Establishing the tile concept was just the beginning and was quite simple. The real engineering problems then began. It was necessary to design thousands of unique tiles which had compound curves, which interfaced with thermal barriers and hatches, which had penetrations for instrumentation and structural access, etc. The overriding challenge then was to assure the strength integrity of the tiles with a confidence that there was no greater chance than 1 in 10,000 of losing any one of the more than 10,000 more critical tiles (i.e., a probability of tile failure of no greater than 1 in 10^8). The statistical treatment of the tile strength integrity is addressed in Ref. 1.

III. Sources of Tile Stress

To accomplish this magnitude of system reliability and still minimize the weight, it was necessary to define the detail loads and environments on each tile. To appreciate the importance and magnitude of this task, one must first examine the sources which induce stresses in tiles. The sources are

- Substrate or structure out-of-plane displacement
- Aerodynamic loads on the tile
- Tile accelerations
- Mismatch between tile and structure at installation
- Thermal gradients in the tile
- Residual stress due to tile manufacture
- Substrate in-plane displacement

The first four are the predominant sources of stress but all must be accounted for, small as they may be, because of the low ultimate allowable tensile stress of 6 psi.

The substrate-induced stress results from the structure deflecting under the tile because of pressure differential across the structure, vibration from engines and aerodynamics, in-plane buckling loads, and thermal gradients. The more compliant SIP accommodates this deflection by stretching but in so doing loads the interface of the tile. The sensitivity of the tile stress, σ_{tt}, to structural deflection, amplitude, δ, and characteristic length, λ, is shown in Fig. 6. The SIP extensional stiffness was established based on reducing this tile stress to an acceptable level, but at the same time retaining the outer moldline and dimensional tolerances, which are important for aerodynamic performance and heating.

The mismatch-induced stresses are manifested also by SIP stretching to accommodate surface differences between the tile and the structure during installation. These differences occur because the surfaces of the machined tile and the surface of the structure to which it is to be bonded are not the same. To preclude this component of tile stress from exceeding approximately 3 psi for a 6-inch by 6-inch tile bonded to 0.160-inch-thick SIP, the mismatch cannot exceed 0.019 inch. Prior to bonding each tile to the Orbiter, it is verified that the allowable mismatch is not exceeded.

The aerodynamic loads on tiles are from very local pressure gradients and shock impingement. Since the tile is internally porous but is coated on five surfaces by impervious glass, it will have an internal as well as an external pressure distribution. The differences in the two distributions results in the net tile load which must be reacted by stress at the tile/SIP interface. Such a pressure distribution is idealized and shown in Fig. 7.

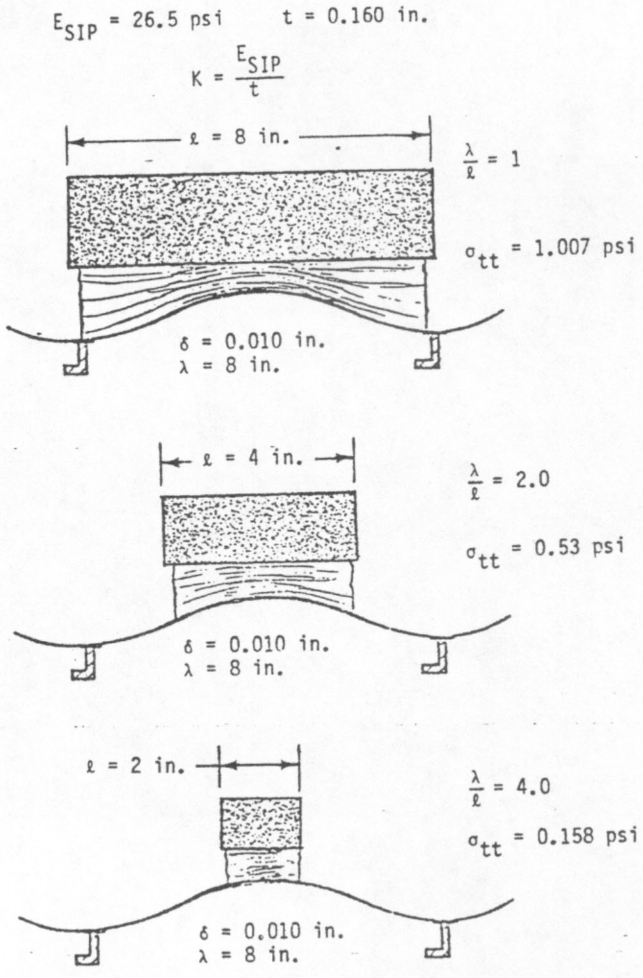

Fig. 6 Effects of substrate deflection.

All significant sources which induce stresses in each tile on the vehicle are considered for each phase of the mission. The matrix of load combinations is shown in Fig. 8.

IV. Verification of Design

Verifying the strength integrity of tiles on a manned spacecraft is not unlike other components whose strength integrity is important and which are exposed to a combination of severe environments. The problem is conducting realistic combined load tests to demonstrate the ultimate strength capability. The prime method of verifying the strength integrity of all tiles was therefore by stress analyses and to test demonstrate where possible. Prior to STS-1, each tile was analyzed for the combination of loads shown in Fig. 8 and resulting factors of safety were compared to the requirements of 1.4 for ascent and 1.0 for the postheating flight regimes. An example of the population distribution of tile strengths is shown in Fig. 9. These results represent linear elastic analyses. To verify that the nonlinear stress-strain properties of the SIP

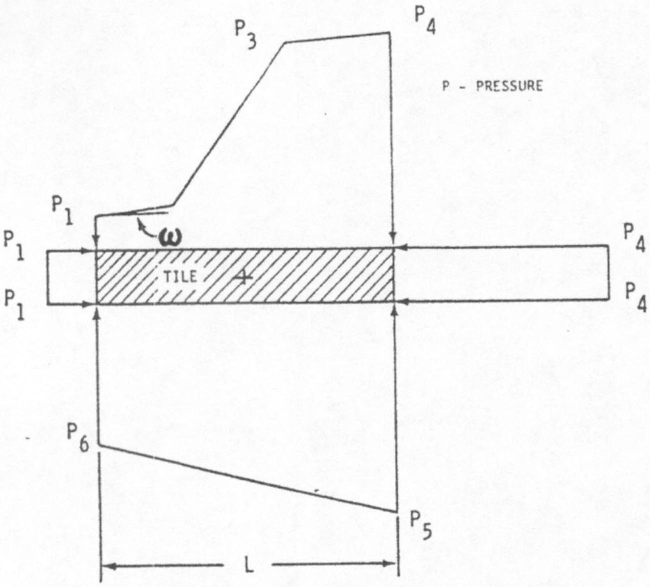

Fig. 7 Aeroshock freebody model for air loads.

	PRE LIFT-OFF		LIFT-OFF	ASCENT		ENTRY / TAEM		LANDING
MIS-MATCH/WARPAGE	X	X	X	X	X	X	X	X
IGNITION OVERPRESSURE								
- SSME	X							
- SRB		X						
AIRLOAD								
- GRADIENT				X	X	X	X	
- SHOCK				X		X		
- VENT LAG				X	X	X	X	
- SKIN FRICTION				X	X	X	X	
VIBROACOUSTICS			X		X		X	
OUT-OF-PLANE DEFLECTION			X	X	X	X	X	X

Fig. 8 Baseline load combinations.

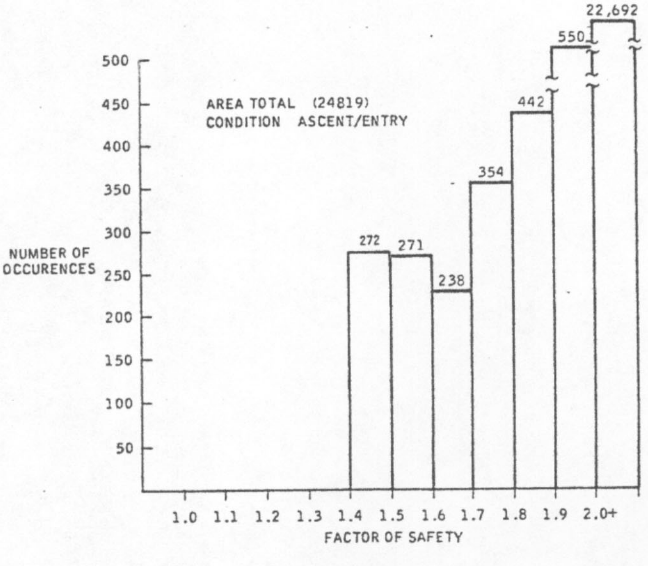

Fig. 9 Factor of safety histogram.

did not result in stresses which violated the strength requirements, separate nonlinear stress analyses were performed on selected tiles which appeared to be the most highly loaded.

Even though the stress analyses were performed on all the more than 30,000 tiles to verify the strength integrity, there was a broad spectrum of tests performed on hundreds of tiles to add confidence to the design, to verify the analyses, and to determine the microscopic load conditions on various regions of tiles. The test articles were selected based on the regions where the analytical methods were suspect, where a single environment (like acoustic vibration) was the predominant load source, and where the tiles were most highly stressed and critical for flight safety.

Aerodynamic Tests

A series of tests was performed with full-scale tiles or arrays of tiles to measure pressure distributions in and around the tiles and to demonstrate the strength integrity of the tiles at 140% of maximum dynamic pressures (approx. 1100 psf). The regions of the Orbiter selected for these aerodynamic tests are delineated in Fig. 10.

A unique approach to aerodynamic tests was used for some of the tile test articles. High-performance aircraft (F-15 and F-104) were used as test facilities (Figs. 11 and 12). Testing full-scale tile arrays to Shuttle ascent conditions in wind tunnels was precluded because of the incapability of available tunnels to achieve the desired conditions. The methods for selecting the test conditions and verifying that same could be attained by the aircraft are discussed in Ref. 2. A summary of some of the aerodynamic test conditions and results is shown in Table 1.

Acoustic Tests

The stresses induced in tiles by the very high acoustic levels (e.g., 165 dB on the aft fuselage region) are the result of dynamic deflection of the spacecraft structure, the acceleration of the tile, and the dynamic properties of the SIP to the random vibration environment. To perform realistic acoustic tests on the tiles, flight-configuration structural test articles were built of the regions of the vehicle shown in Fig. 13 and tested in acoustic chambers at flight conditions. This series of acoustic tests, which also had primary structure fatigue certification objectives, served to satisfy both strength integ-

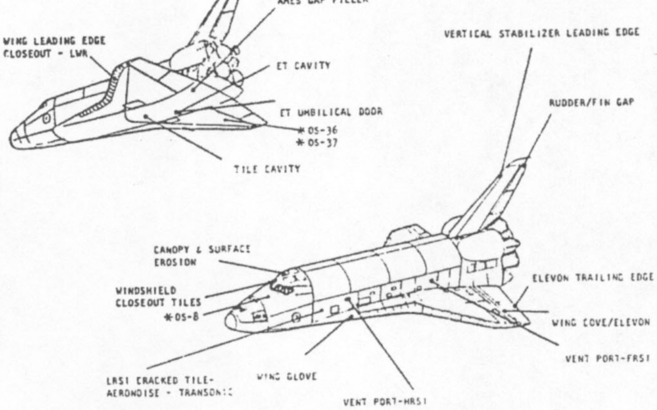

Fig. 10 TPS flow test program test article locations.

Fig. 11 DFRC in-flight aerodynamic load testing of Shuttle TPS.

rity objectives and SIP life and extension objectives. The results of the tests are summarized in Table 2.

Combined Loads Tests

A series of combined loads tests was conducted at NASA Langley Research Center. Two of the tests, which were a constraint to the STS-1 flight, were performed to demonstrate the integrity of the tiles, to verify analyses, and to determine the dimensional stability of the tiles in the complex aerodynamic environment region around the forward structural attachment between the Orbiter and the External Tank. The tests were performed in a 16-foot transonic wind tunnel at freestream dynamic pressures up to 750 psf and speeds up to Mach 1.4. The structural panel had imposed on it the combined effects of pressure differential across the skin, the local aerodynamic pressure gradients and noise, and the low frequency vibration (induced with shakers below the wind tunnel). The test article locations which successfully passed multiple mission exposures are shown in Fig. 14.

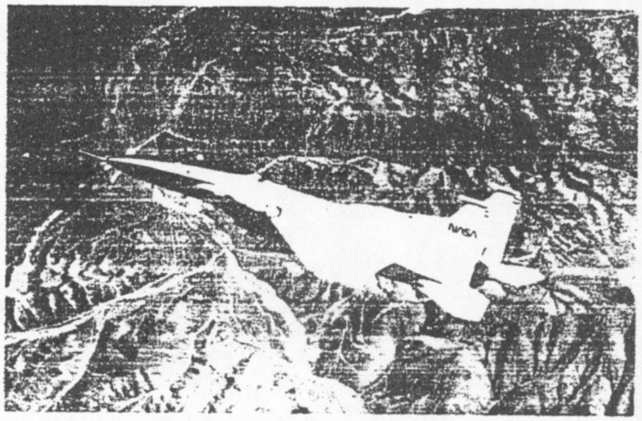

Fig. 12 F-15 test of tiles on wing leading edge and glove.

The other combined loads tests conducted at Langley were fatigue tests required to clear the undensified tiles for the STS-1 flight. The densified tiles and SIP had demonstrated good durability and fatigue resistance by other wind tunnel, acoustic, and vibration tests. The durability of the SIP is shown in Fig. 15.

The challenge on the undensified tile fatigue test was to conduct a realistic test (not overly conservative) with simulated steady-state loads due to aerodynamic pressure gradients and shocks and structural deflections, and then superimpose simulated vibration loads due to engine and aerodynamic noise. The tests were performed using the test setup shown in Fig. 16 with the static and dynamic load sequence shown in Fig. 17. All tiles tested which represented the critical undensified tiles under the wing and midfuselage successfully passed the test. The results showing the residual strength after withstanding equivalent to 72 missions of exposure are shown in Table 3. The load tests consisted of 8-psi proofing, 72 ascent mission dynamic loading (30 minutes), 8-psi reproofing, and pulling to failure. The column of proof test results means the tile failed an acoustic emission criterion which is discussed later.

V. Verification of Flight Hardware

The final step of ground tests to verify the strength integrity of the *Columbia* tiles dealt with the actual tiles bonded on the spacecraft, whereas the tests discussed previously were generic tests, which served to verify the design. The tests performed on the *Columbia* tiles were

- o Proof tests to demonstrate a required strength capability
- o Acoustic emission (AE) monitoring to assure that the damage induced by proof tests was not excessive
- o Pulse velocity tests (PVT) to determine the lower bound strength of the densified RSI

Table 1 Aerodynamic tests

Description	Test facility	Test conditions	Results
Elevon trailing edge	F-104	Max Q = 455 psf	No anomalies.
ET umbilical cavity	AEDC 16 ft	Max Q = 900 psf	Thermal barrier frayed, tiles under crossbeam loosened and baggie retainer cord damaged tile OML. Redesigned hardware tested with no anomalies.
Canopy diced tile	Ames 11 ft	Max Q = 750 psf	Three tiles came off and several loosened. Pretest OML damage did not propagate. Re-test with mini tile edges bonded to filler bar was successful.
Wing leading edge closeout	F-15	Max Q = 1140 psf	Gap filler (horsecollar) migrated beyond OML and tiles showed excessive deflection. Redesigned horsecollar and tile support successfully tested.
Wing glove	F-15	Max Q = 1140 psf	No gap filler migration and tile step and gap change less than predicted. Test successful.
ET umbilical door	AEDC 16 ft	Max Q = 800 psf	Flow restrictors failed in initial test. Redesign successful.
Vent port-FRSI	Ames 11 ft	Max Q = 970 psf	No anomalies.
Vent port-HRSI	Ames 11 ft	Max Q = 970 psf	Limit and ultimate load portion complete. After ultimate condition was reached, portion of aft tile came loose. Life testing to continue.
Windshield closeout tiles	F-15	Max Q = 1140 psf	Initial tests indicated high net airloads. Redesign tested. No anomalies.
Wing cove/elevon	F-104	Max Q = 1125 psf	No anomalies.
Shaved tile/ mini gap fillers	Ames 11 ft	Max Q = 650 psf	No anomalies.
Vertical tail leading edge	F-15	Max Q = 1140 psf	No anomalies.
CLOT-fwd fuse acreage-calib panel	LaRC 8 ft	Over 90 min of shock from bi-pod	No anomalies.

- o <u>Bond verification tests</u> to demonstrate the strength of the bonded interface to nominal stress levels

All of these test methods were developed for the tiles in order (1) to utilize the inherent strength capabilities of the as-manufactured and installed tiles as opposed to using a more conservative lower bound material system strength, (2) to demonstrate that thousands of the already installed and undensified tiles with low flight-induced stresses were adequate and did not require densification prior to STS-1, and (3) to save cost and schedule.

At a point when all of these test methods were developed, the Orbiter tiles were partially installed, there were both densified and undensified tiles, there were critical and noncritical tiles (i.e., loss of a single tile would not result in excessive structural temperatures), and there were large thin tiles which failed-safe because the critical flight-induced through the thickness stresses were reduced by the first noncritical failure (breaking into smaller segments). In order to determine what action should be taken to which tile to demonstrate the required strength integrity for the Orbiter Flight Test (OFT) series (STS-1 through STS-4), a rather complex logic path was followed (Fig. 18).

The proof tests loaded individual tiles in uniform tension to stress levels nominally equivalent to 125% of the maximum predicted flight-induced stress. Mismatch stresses did not have to be considered in determining the proof-stress requirement because the mismatch condition either existed or did not exist on a specific tile. The proof test also eliminated the consideration of mismatch stress for all subsequent load conditions at lower stress levels. The reason for this

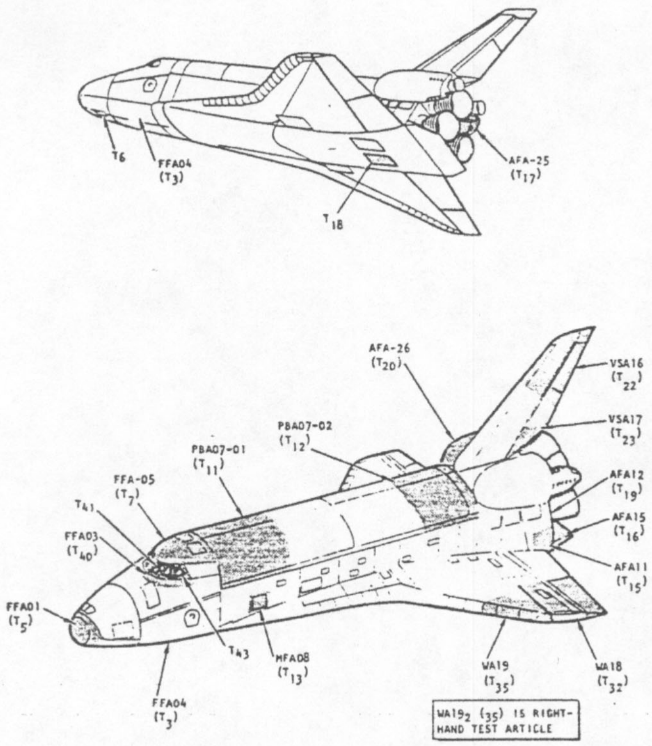

Fig. 13 Qualification test specimen locations.

Table 2 Acoustic tests

Description	No. of tiles	Missions	Results
Fwd fus lwr pnl (FFA-04)	LI 900 {13-D[a] 81-U[b]	6	No tile failure.
Mid fus side access pnl (MFA-08)	LI 900 ~50-U	100	No tile failure.
Body flap (AFA-15)	LI 900 {51-D 118-U LI 2200 17-D	25	No tile failure < 25 mission coating chips between tiles.
Aft RCS TPS instal (AFA-25)	LI 900 43-U	100	No tile failure.
OMS pod (AFA-26)	LI 900 58-U LI 2200 15-U	31	No tile failure.
Vert stab upper half (VSA-16)	LI 900 77-U LI 2200 24-D	4	No tile failure.
Fwd fus lwr pnl (DA-7)	LI 900 243-U	100	No tile failure.
Fwd fus shoulder (DA-34)	LI 900 152-U	100	No tile failure.
Wing L. E. system	-	100	Some acreage tiles were rejected tiles but did not have any tile loss.

[a] D is densified tile.
[b] U is undensified tile.

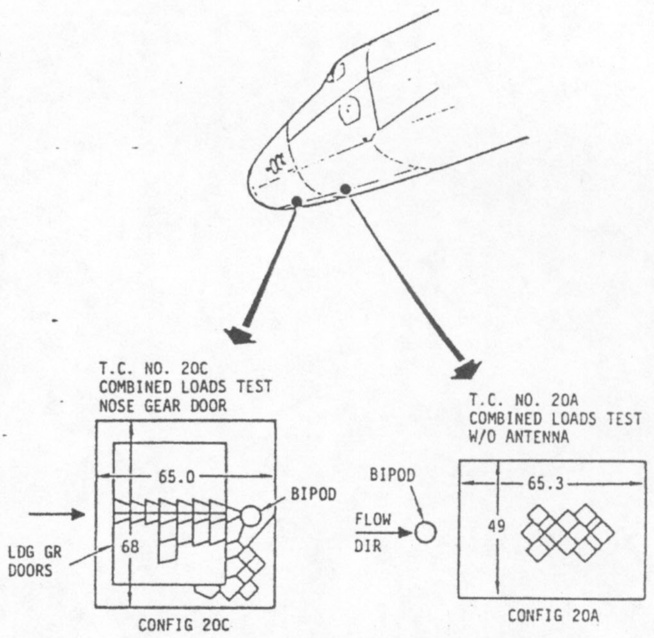

Fig. 14 Combined loads Orbiter tests: test article configuration.

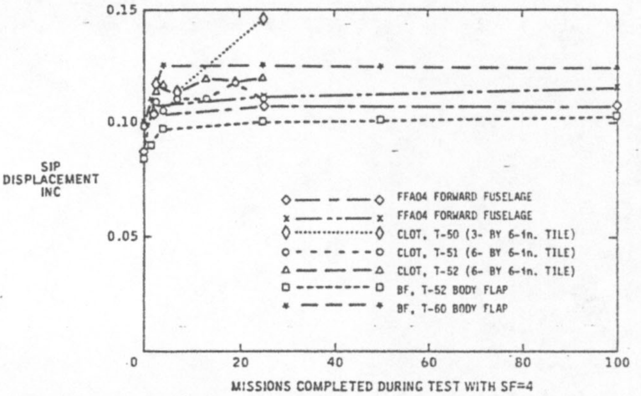

Fig. 15 Total SIP excursion, -4 to 6 psi, during test.

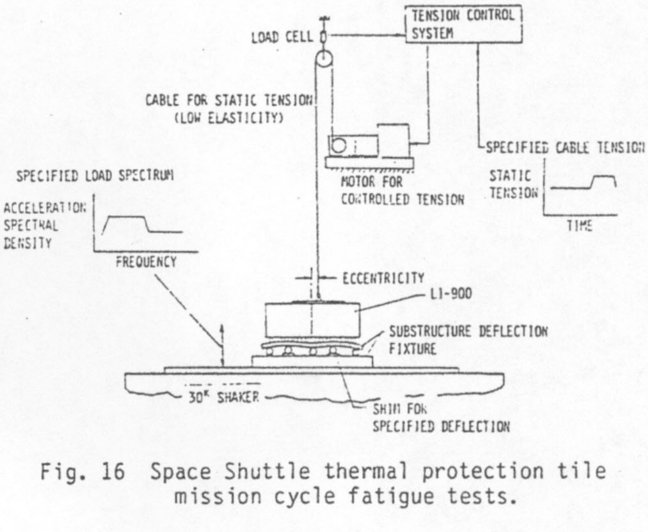

Fig. 16 Space Shuttle thermal protection tile mission cycle fatigue tests.

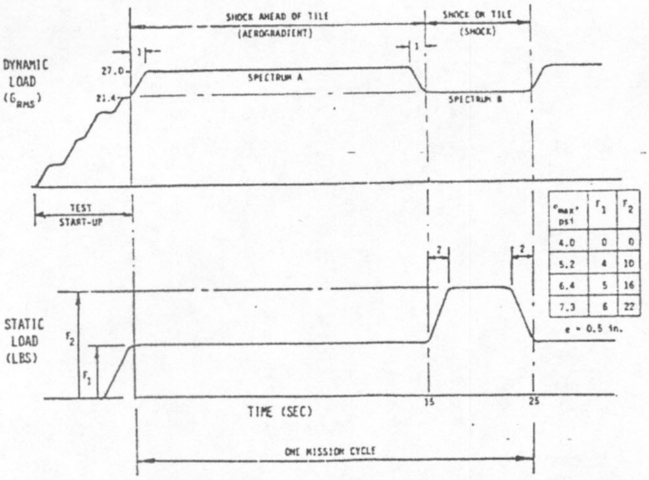

Fig. 17 Static and dynamic load sequence for W-3 tests.

Table 3 Load tests

Specimen no.	Nominal maximum dynamic loading, psi	Passed/failed proof[a] after dynamic tests	Residual strength, psi
1	7.3	Failed	9.3
2	7.3	Failed	11.7
3	7.3	Passed	12.0
4	7.3	Passed	14.3
5	6.4	Passed	11.0
6	6.4	Passed	11.7
7	6.4	Passed	12.6
8	6.4	Passed	13.6

[a] Acoustic emission criteria.

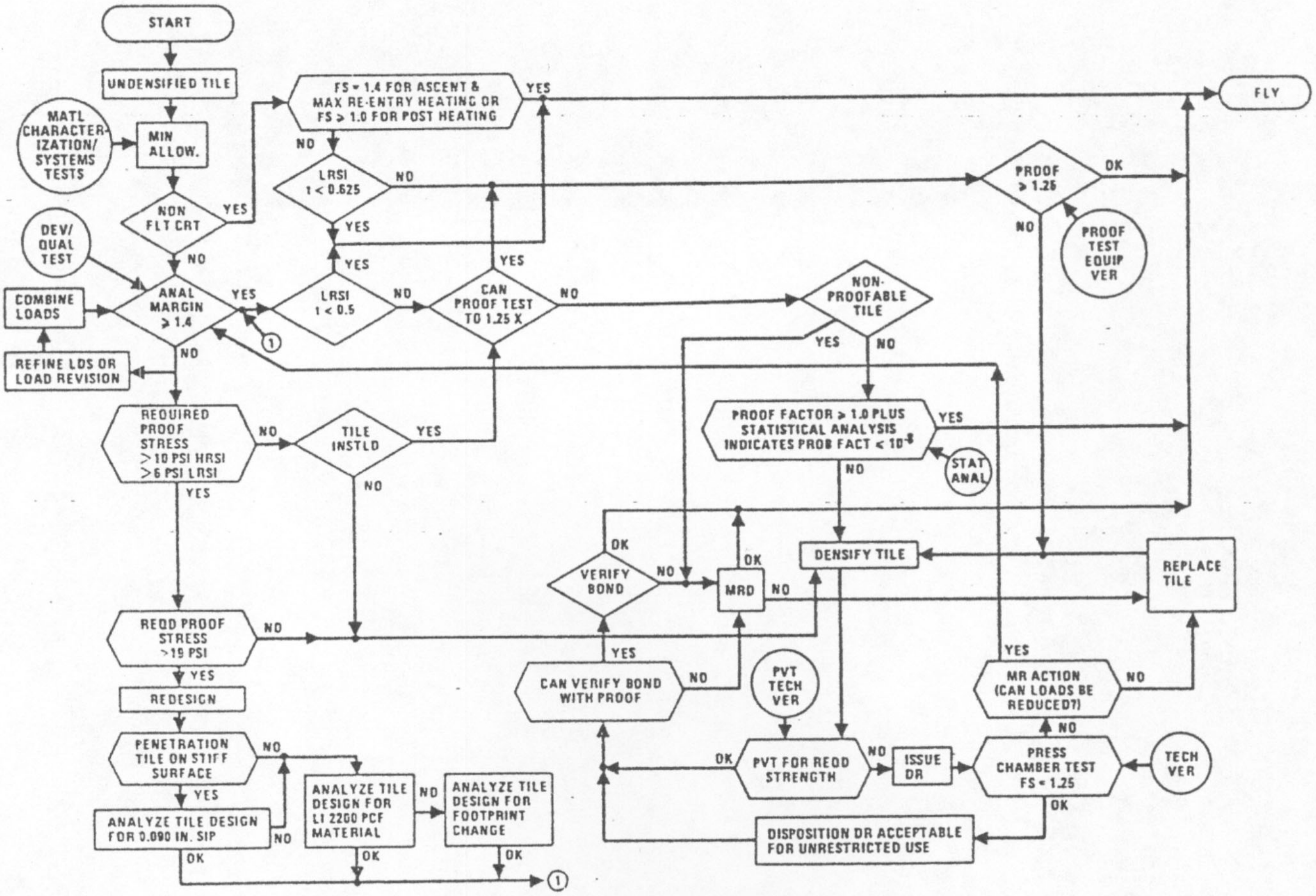

Fig. 18 Tile system acceptance logic diagram: HRSI LI-900 (STS-1).

was that a successful proof test stretched the SIP in the region of the mismatch so that the extensional modulus was greatly reduced and it would, for a given displacement, generate a greatly reduced stress. An example of this effect is shown in Fig. 19.

VI. Results of STS-1

From the point of view of tile strength integrity, the maiden flight of the Orbiter was an *outstanding success* for all but 16 of 30,757 tiles. One complete tile and 15 small segments were lost during ascent. These lower temperature, undensified tiles on the Orbital Maneuvering System (OMS) propulsion structure were damaged during late processing (cutting into smaller segments) after being installed on the vehicle and did receive the rigorous bond verification. This damage was proven, after flight, to be the cause of failure. The tiles in this area have since been densified and the bond area increased, and should not experience another strength failure.

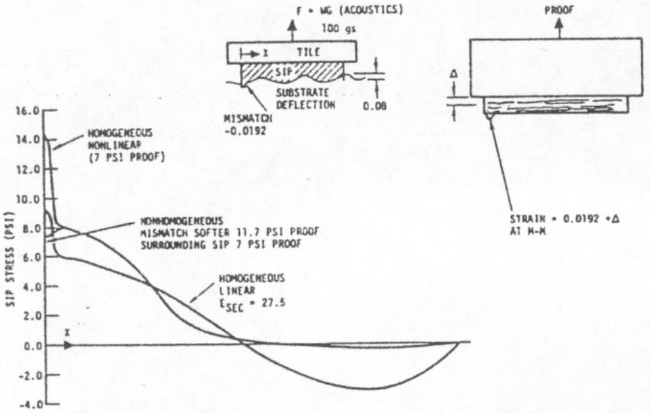

Fig. 19 Proof test eliminates effect of mismatch stress.

VII. Concluding Remarks

Although the tile coating is susceptible to handling damage, the TPS has been proven to be an efficient, lightweight, and durable system. Development is continuing, but without major changes. The next Orbiter, *Challenger*, will have all tiles densified, and improved, lighter material for those few tiles requiring high strength, and a larger area of flexible insulation.

The first flight test of the *Columbia* was truly the successful culmination of a large and challenging engineering endeavor for developing this reusable Thermal Protection System.

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2. "In-Flight Aerodynamic Load Testing of the Shuttle Thermal Protection System," AIAA First Flight Test Conference, Nov. 11-13, 1981, Paper AIAA 81-2468.