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SPACE SHUTTLE ORBITER REUSABLE SURFACE INSULATION FLIGHT RESULTS

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SUMMARY

The first five flights of the orbiter Columbia have provided the initial data required to certify the operational performance of the reusable surface insulation (RSI) thermal protection system (TPS). This paper discusses the flight performance characteristics of the RSI TPS. This discussion will be based primarily on postflight inspections and postflight interpretation of the flight instrumentation. TPS modifications of the future orbiters (OV-099, 103, and subs) will also be discussed.

INTRODUCTION

The orbiter thermal protection system (TPS) must protect the primary vehicle structure and other subsystems from the severe aerothermodynamic conditions associated with entry into the Earth's atmosphere. In order to minimize design and development costs, the orbiter vehicle utilized standard aluminum fabrication techniques with the exception of the cargo bay doors and orbiter maneuvering system pods in which the lightweight graphite-epoxy structure was used. Use of these structural materials which have relatively low temperature capability (<350°F) necessitated the design and development of lightweight, thermally efficient thermal protection materials.

A major constraint on the use of conventional TPS materials (such as the ablators or metallic systems that existed in the late 1960's) was the requirement for 100-mission reuse in the oxidizing entry environment at temperatures exceeding 2000°F. Based on these unique requirements, the most promising class of materials at the time was the ceramics; this class is virtually insensitive to the deteriorating effects of oxidation. After considerable development activity, the rigidified silica TPS evolved, which possessed a stable chemical structure along with the unique thermal properties required for a minimum weight TPS.

Five successful flights of the orbiter Columbia have provided the initial data to verify the thermal performance, structural integrity, and reusability of the tile TPS. Overall, the silica tile TPS has performed remarkedly well after multiple exposures to severe natural environmental conditions as well as the induced thermal and load environments. There have been some minor localized areas of the orbiter in which heating exceeded expectations; however, these areas have been amenable to design corrections, and vehicle turnaround has not been adversely affected. The amount of TPS refurbishment activities between flights is approaching the

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level of effort required to meet operational vehicle turnaround timetables.

This paper will provide a brief description of the design characteristics of the TPS tile system, a summary of the design goals and requirements, the principal findings of the flight test program, and future TPS changes.

SYSTEM DESCRIPTION

The reusable ceramic tile TPS has evolved after more than a decade of dedicated development activity by both governmental and industrial organizations. This unique TPS material, which is used on ~70% of the external surface of the orbiter Columbia, is manufactured in two forms. The lower density form (termed LI-900) has a nominal density of 9 lb/ft^3, the higher density form (termed LI-2200) has a nominal density of 22 lb/ft^3. These materials are fabricated in the form of tiles covered with an external borosilicate glass coating. Two types of coatings are used on the LI-900 tiles. A black version with good high-temperature emittance is used on the lower surface of the orbiter, and a white version with low solar absorptance for orbital thermal control purposes is used on the upper surfaces of the orbiter. The tiles are then bonded to a strain isolation pad (SIP), and then the SIP is bonded to the orbiter structure. Figure 1 shows the installed tile/SIP configuration. The other reusable surface insulation material (termed flexible reusable surface insulation (FRSI)) is the simplest TPS material on the orbiter and consists of a needled nylon felt material that is coated with a thin silicone elastomer film. Locations of the various thermal protection materials that are applied to the orbiter Columbia structure are shown in figure 2. The material characteristics and detailed descriptions of the design applications have been presented in references 1-3.

DESIGN REQUIREMENTS

The application of the relatively brittle silica tiles for the orbiter TPS necessitated innovative design approaches. The key factor of the design was the requirement to operate satisfactorily for 100 missions with minimal maintenance or refurbishment.

The TPS is designed for the entry thermal environments that encompass mission parameters such as the orbit inclination, vehicle entry angle of attack, attitude, size of payload (e.g., total entry weight), and downrange and crossrange emissions. The TPS design mission is known as mission 3A normal-nominal ascent, single-orbit polar mission, and mission 3B entry. The design trajectory for this mission (14414.1c) was used to initially size the orbiter TPS and resultant outer mold line. Figure 3 illustrates the predicted maximum temperature distributions on the surface of the orbiter during the entry phase of the design mission. Figure 4 compares the design entry mission maximum reference heating rate and heat load with the STS-1 thru -5 mission reference values. As can be seen, the STS-1 thru -5 missions were ~10-15% lower than the design mission in heat load and ~5-30% lower in maximum heating rate. Later missions are planned to verify the design mission capability.

The RSI tile is an excellent thermal insulation and is designed to reradiate a majority of the entry heat back to space. To perform its intended thermal function, the TPS must also sustain the other induced environments such as the launch vibroacoustics and structural deflections, on-orbit cold soak, and exposure to the natural environments of wind and rain.

To insure that each tile maintains its structural integrity and attachment to the vehicle structure, the vehicle loads were defined, then the detailed loading mechanisms which induce critical stresses in the tiles were identified, followed by detailed stress analyses which predicted the flight margins for each tile. The various sources of tile stresses, the stress analysis methodology, descriptions of the various structural integrity tests and verification activities are described in reference 4.

FLIGHT TEST PROGRAM RESULTS

Five successful flights of the orbiter Columbia have provided significant thermal-structural performance data as well as reuse characteristics of the silica-tile thermal protection system. The primary trajectory parameters (i.e., altitude, velocity, and vehicle angle of attack) during the five flights have been relatively similar with the exception of control surface deflections. The flight data is available in the form of thermal responses from the development flight instrumentation and from observations during the detailed postflight inspections conducted at the landing sites and at the Kennedy Space Center (KSC).

THERMAL PERFORMANCE

Thermal performance data was obtained during each of the five flights of the orbiter Columbia. Complete entry data was obtained only during STS-2, -3, and -5 due to recorder malfunctions during the STS-1 and -4 flights. Partial data was obtained during the STS-1 and -4 flights by data transmission to a ground station after the entry blackout period. The basic TPS thermal response data is obtained primarily from thermocouples located on the tile surfaces, at various depths in the tile, at various locations on the tile sidewalls, and at numerous locations on the orbiter structure.

Sufficient data has been acquired to describe the primary aerothermodynamic characteristics of the orbiter configuration for the conditions under which it has been flown. In general, transition effects have occurred later than expected. The surface temperature distributions and magnitudes that occurred during entry were within expected ranges. However, there were some localized areas where surface temperatures exceeded the design thermal limits of the TPS materials. Figure 5 shows an area of FRSI that experienced overtemperature conditions on the aft side of the OMS Pod. Figure 6 shows an area of FRSI that experienced overtemperature conditions on the side of the payload bay doors.

Gap heating in a number of locations was more severe than predicted. The excessive gap heating resulted in some cases of tile sidewall shrinkage, filler bar overtemperature (charring), and in one case, localized severe structural temperature gradients. Extensive test programs were undertaken at JSC to reproduce the filler bar charring observed during the flights and to demonstrate that the vehicle corrections (i.e., partial gap filler installations) would perform satisfactorily. Refined numerical solutions as discussed in reference 5 were also conducted to understand the complex physical phenomena that were involved.

Heating levels on the lower forward fuselage were ~200-300°F lower than predicted. This is attributed to the noncatalytic characteristic of the coated tiles. With the lower surface energy input into the tiles on the lower surface, the structural temperatures responded accordingly. In addition, an internal structure convective cooling phenomenon was observed. This effect started late in the entry (Mach = 2.5) when the orbiter vent doors opened. In some areas, the effect suppressed the structural temperature response by as much as 20°F. Peak surface temperatures for STS-2, -3, and -5 are shown in figures 7-9. Structural temperature rise data from all five flights are shown in figures 10-12. In general, consistent performance has been observed. When surface temperature is used as an input factor in math models, good agreement between flight data and analyses is obtained as shown in figures 13-15.

STRUCTURAL PERFORMANCE

The structural integrity of the tile and its attachment system has been excellent during the flight test program. None of the critical black tiles on the lower surface of the orbiter has been lost. Some undensified OMS pod tiles were lost (figure 16) during STS-1. This was due to improper machining operations performed during operations at KSC just prior to STS-1. There was also a loss of some undensified tiles during STS-3 on the upper forward fuselage area (figure 17) and upper body flap (figure 18), which was determined to be due to excessive use of the tile rewaterproofing material. In general, however, it can be said that the strength integrity of the tile and its attachment system has been adequate for the induced environments experienced to date.

MOISTURE

Early in the TPS development, prevention of moisture entrapment and/or moisture absorption after exposure to the natural environment at the launch site was recognized as a particularly difficult problem. After extensive development efforts, the best exterior water repellant material was selected for use on the orbiter. During the STS-2 thru -5 flights, this material has shown marginal performance in view of the loss of portions of tiles due to moisture absorption during STS-2, loss of undensified tiles on the upper surfaces of the vehicle during STS-3 due to the effects of the water repellant material solvent, and excessive moisture absorption prior to the STS-4 launch.

TILE DAMAGE AND REMOVAL EXPERIENCE

The numbers and causes for removal of tiles that have occurred during the turnaround activities at KSC are shown in table 1. The number of tiles requiring removal between succeeding flights is declining and is less than the levels projected for the operational program. The majority of the tiles that have been damaged during the ascent phase by various debris sources have shown no adverse degradation of their thermal performance. Most of the tile damage has been readily repairable by means of ceramic filler agents or silica slurry materials that are brushed on. The flight data to date indicates that these repairs have multimission life capabilities.

TPS CHANGES FOR FUTURE ORBITERS

During the fabrication of the orbiter Columbia, considerable difficulty was experienced in the installation of the thin, relatively fragile, white tiles, particularly on the front of the highly curved OMS pods. This led to use of a relatively new TPS material called flexible insulation (FI) on the OV-099 OMS pods instead of the white tile used on the Columbia. The FI, flexible silica cloth insulation blanket development is discussed in reference 6.

Virtually all the white tile will be replaced with FI blankets on the OV-103 and 104 orbiters. The higher heating on the sides of the fuselage and on the OMS pods noted during the OFT program was factored into the FI thickness design for OV-103 and OV-104. This should allow the OV-103 and OV-104 orbiters to fly the hotter western test range (WTR) missions.

Another change incorporated in the OV-103 and OV-104 design was use of another relatively new TPS material, called fiber reinforced composite insulation (FRCI-12), instead of the high-density LI-2200 tile. Reference 7 describes the development of this lightweight high-strength tile material.

CONCLUDING REMARKS

The thermal/structural performance of the reusable surface insulation TPS during the first five flights has been better than our most optimistic projections. The structural attachment of the critical black tiles on the lower surface has been excellent, and no adverse degradation of the tiles or the attachment system has occurred. There have been localized overtemperature conditions experienced on the upper surface which have necessitated minor repairs to the TPS during the ground turnaround operations. Also, excessive gap heating conditions occurred in a number of gaps on the lower surface and required minor turnaround refurbishment. However, all of these problems areas have been amenable to either design corrections or turnaround repairs, and satisfactory performance is expected during the operational flights. Tile refurbishment and replacement have been at the levels of effort projected for the operational flights. The advanced TPS materials that will be used on future orbiters should upgrade TPS performance to the levels required for the WTR missions as well as lower the amount of refurbishment activities required between flights.

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TABLE 1.- POSTFLIGHT TPS TILE REMOVAL SUMMARY

		POST STS-1	POST STS-2	POST STS-3	POST STS-4	POST STS-5**
RELATE TO OPERATIONAL TURN-AROUND	INFLIGHT DAMAGED	247	109	113	122	119
	LOOSE (DETECTED BY EXCESSIVE STEP)	158	18	15	3	6
	SCORCHED FILLER BAR	246	47	39	36	10
	GROUND DAMAGED	55	13	41	44	36
	FAILED PULL TEST AFTER RE-INSTALLATION	17	7	0	5	1
	SUB TOTALS	723	194	208	210	172
OFT UNIQUE	INSTRUMENTATION REWORK	73	13	3	4	0
	FLIGHT EXPERIMENTS	20	11	11	2	0
	ENGR. MODIFICATIONS	52	17	0	12	215
	ASSESS FOR STRUCTURAL EVAL/ REWORK	72	8	22	17	34
	ENGR. EVALUATIONS	* 22	21	18	26	14
	MISCELLANEOUS	59	5	2	3	0
	DENSIFICATION OF TILES NOT DENSIFIED PRIOR TO STS-1	526	202	783	0	1239
	TOTALS	***1547	471	1047	274	1674

*NOTE 1 - MANY INCLUDED IN MISC CATEGORY FOR POST STS-1 TURNAROUND

**NOTE 2 - AS OF 2/7/83, TURNAROUND ACTIVITY NOT COMPLETE

***NOTE 3 - DOES NOT INCLUDE THE 379 TILES THAT REQUIRED REINSTALLATION AS A RESULT OF THE N_2O_4 SPILL THAT OCCURRED JUST PRIOR TO STS-2

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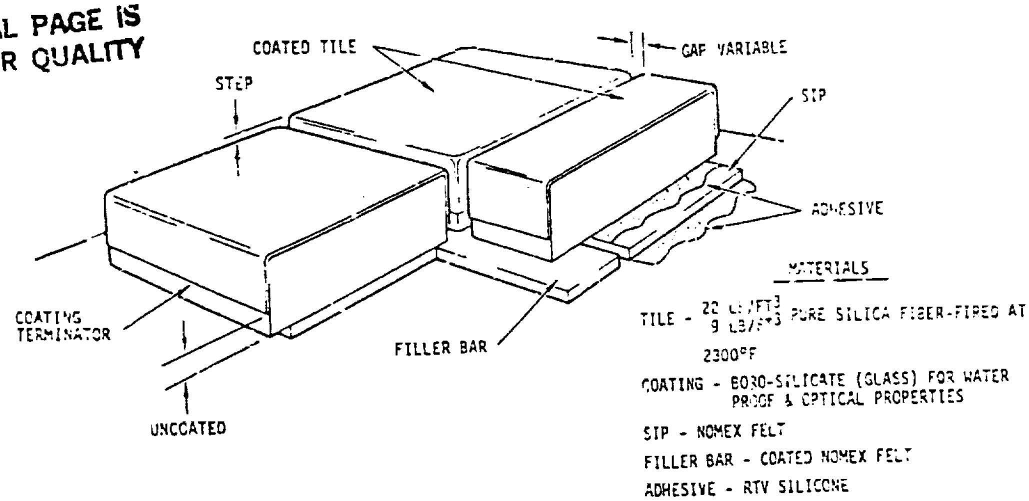

Figure 1.- Tile system configuration.

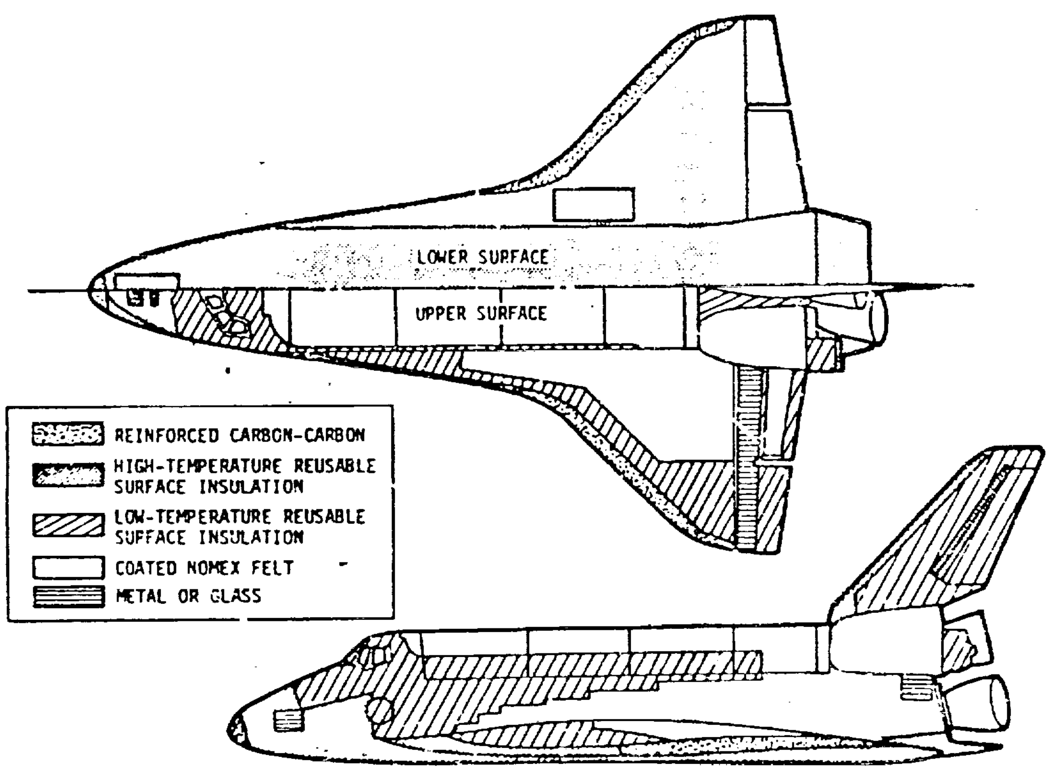

Figure 2.- Thermal protection subsystem.

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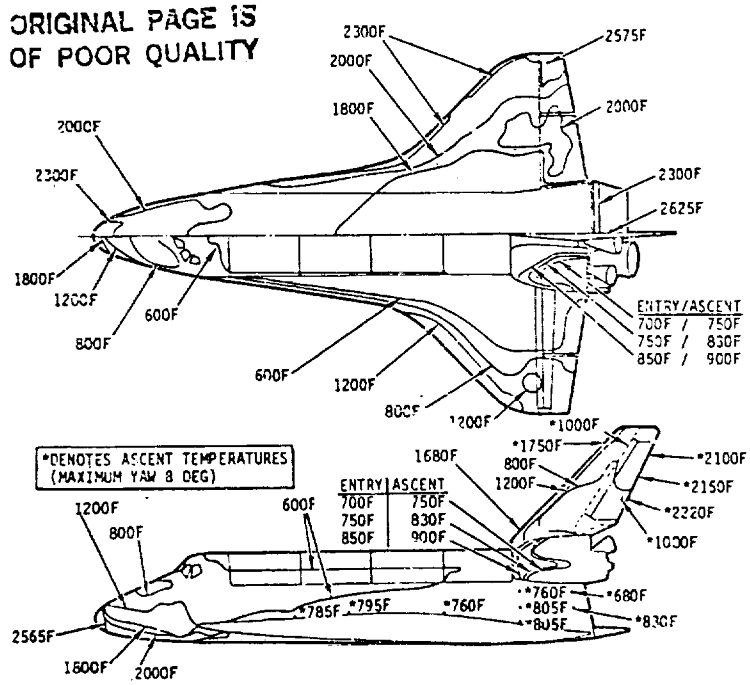

Figure 3.- Orbiter design entry isotherms.

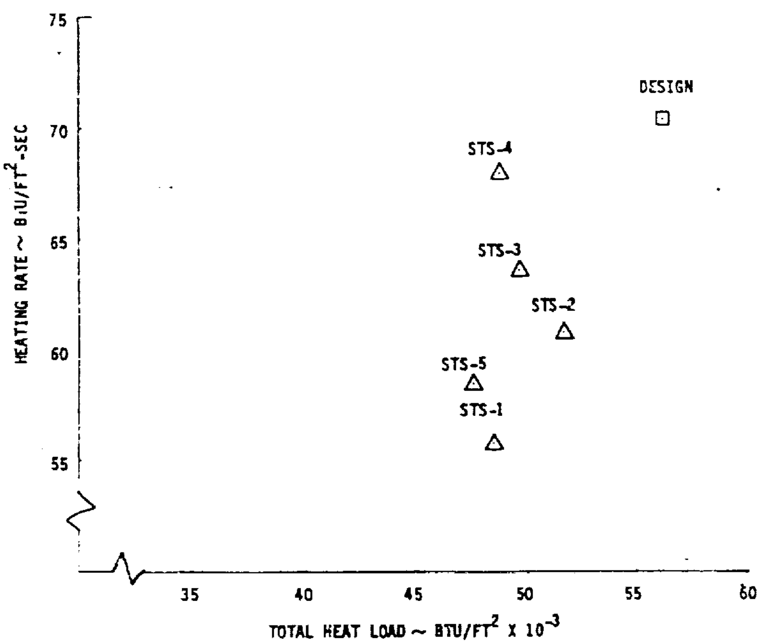

Figure 4.- Comparison of reference heating conditions (design versus STS-1 thru STS-5).

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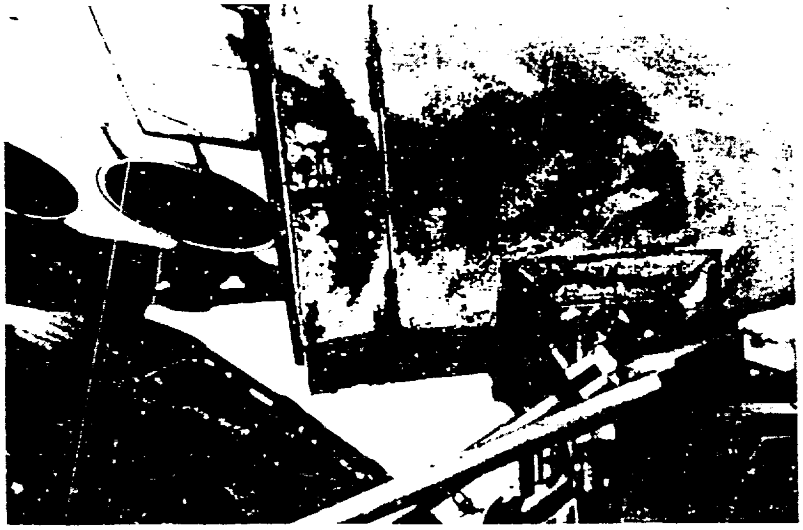

Figure 5.- Overtemperature areas of FRSI on lower trailing edge of OMS pod - STS-1.

Figure 6.- Overtemperature areas of FRSI on payload bay door - STS-1.

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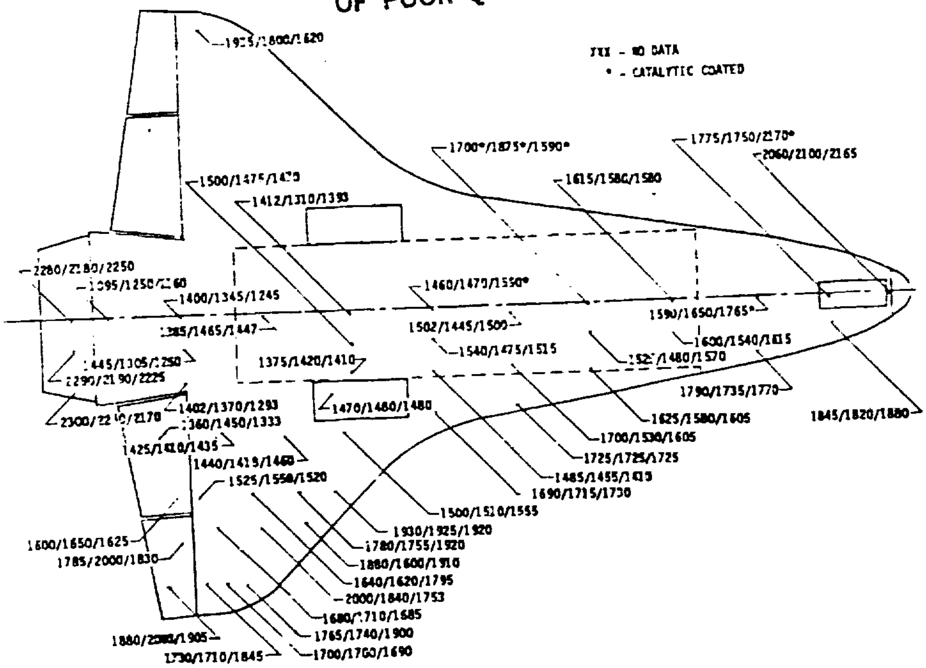

Figure 7.- Orbiter TPS peak surface temperatures, STS-2/STS-3/STS-5.

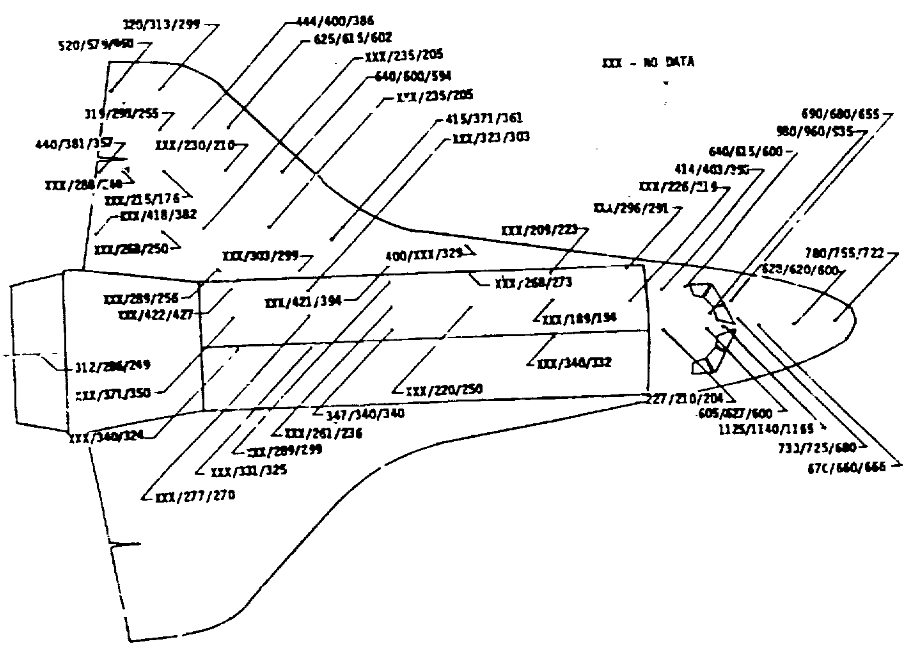

Figure 8.- Orbiter TPS peak surface temperatures, STS-2/STS-3/STS-5.

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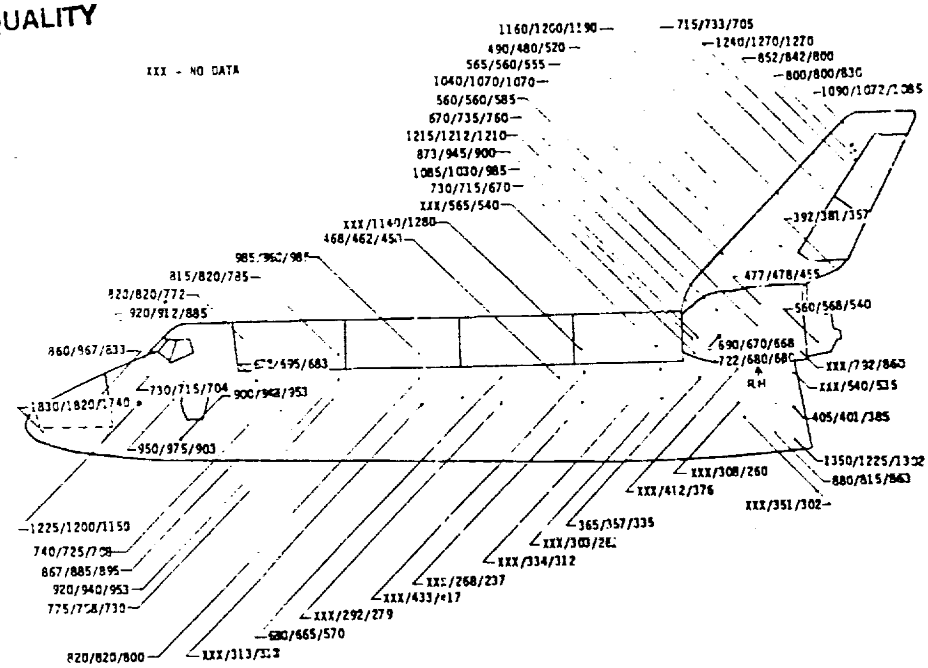

Figure 9.- Orbiter TPS peak surface temperatures, STS-2/STS-3/STS-5.

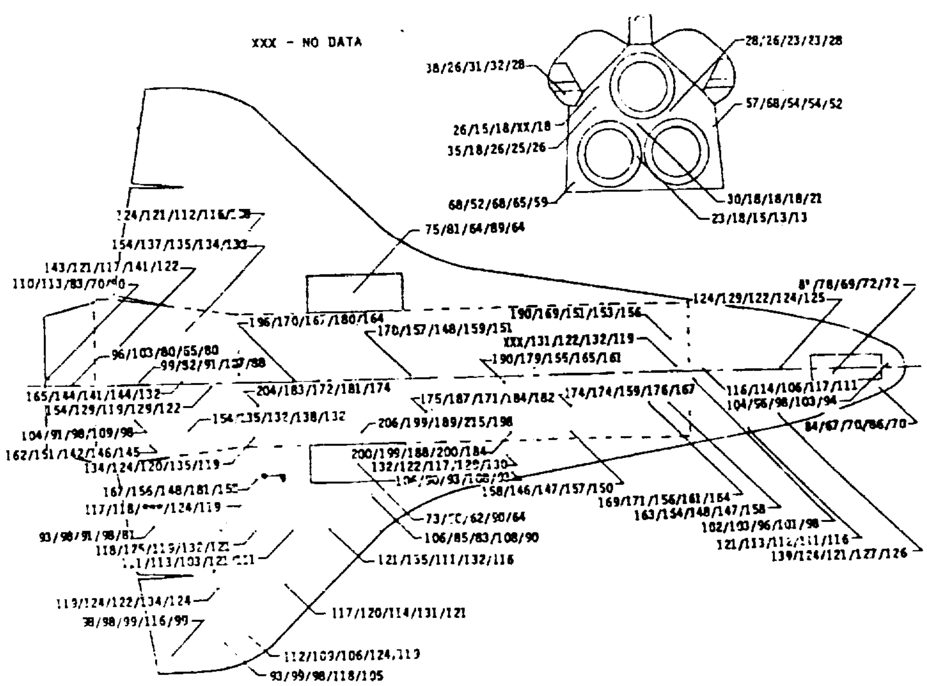

Figure 10.- Structural temperature rise resulting from entry heating (STS-1 thru STS-5).

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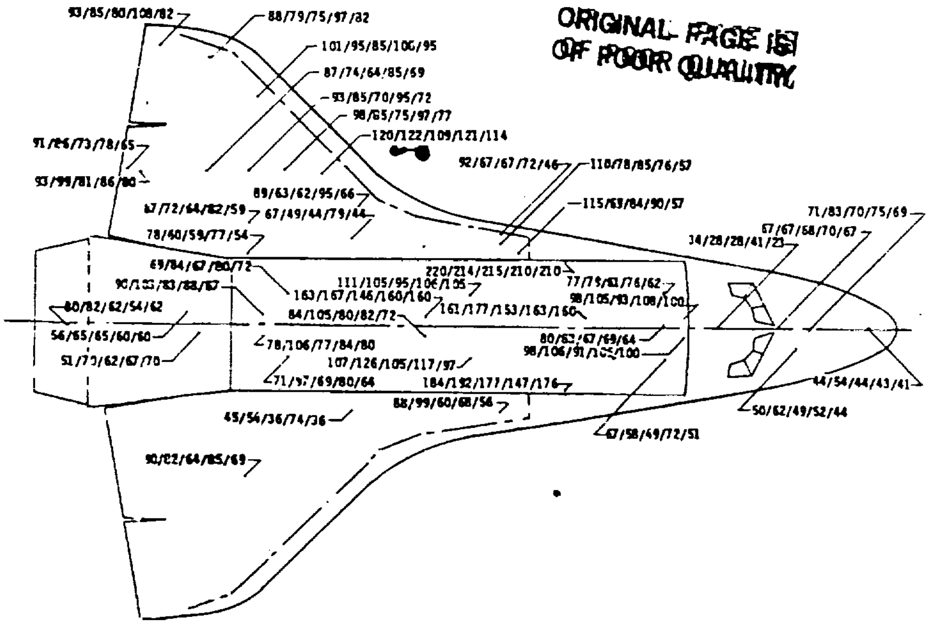

Figure 11.- Structural temperature rise resulting from entry heating (STS-1 thru STS-5).

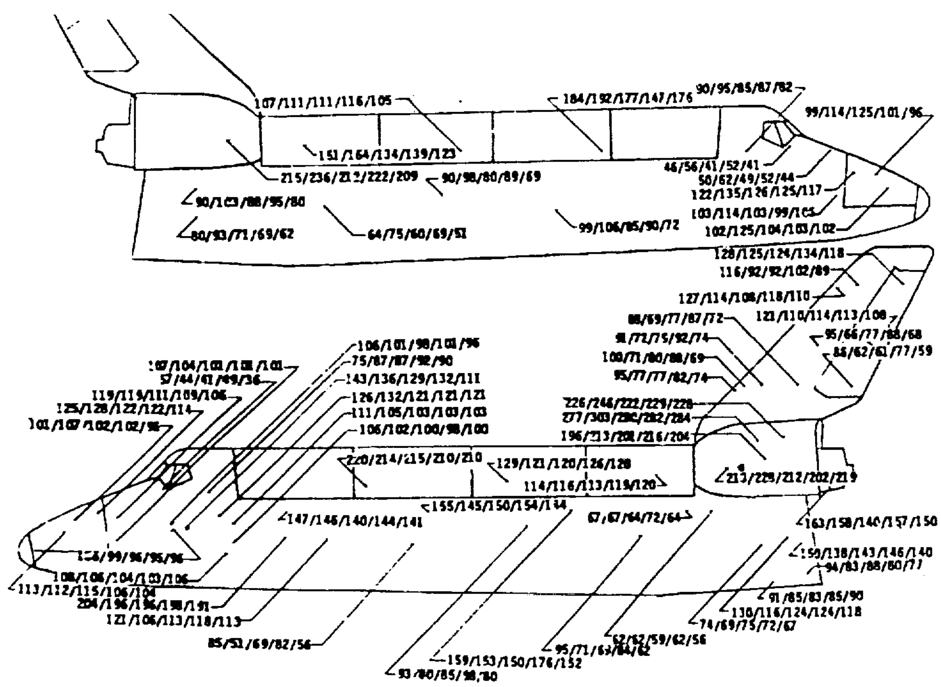

Figure 12.- Structural temperature rise resulting from entry heating (STS-1 thru STS-5).

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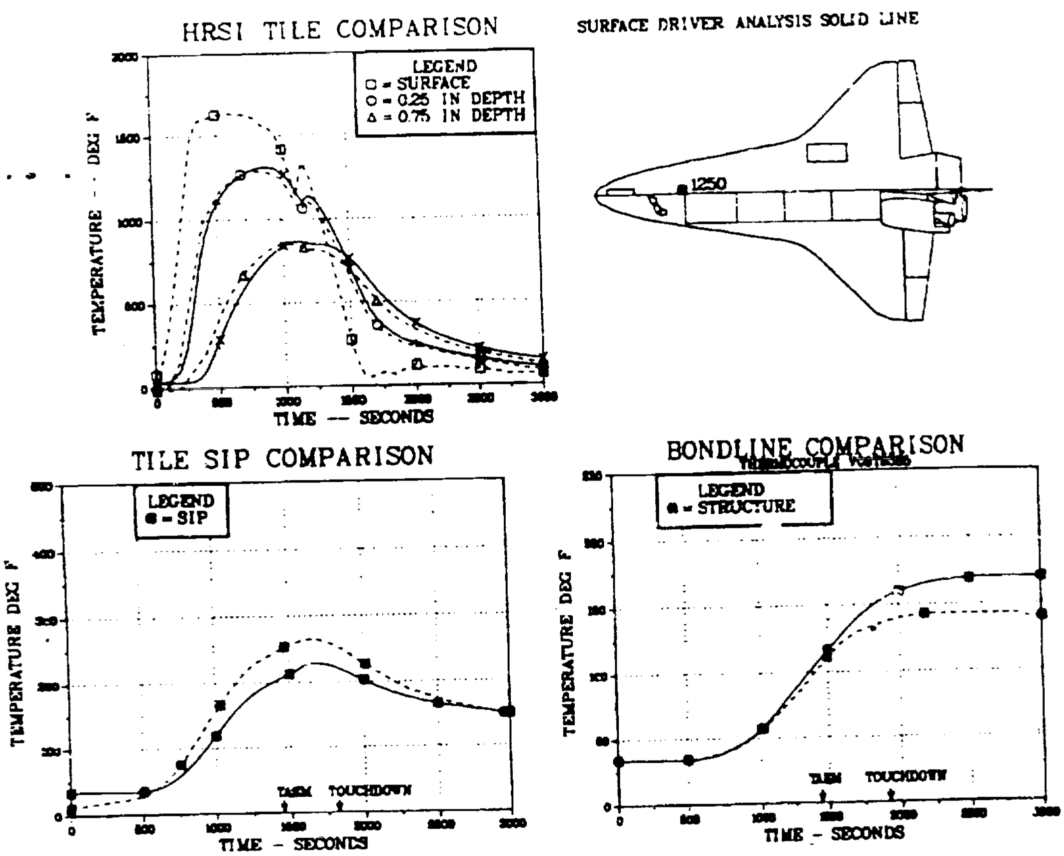

Figure 13.- STS-5 comparison of flight data versus analyses - body point 1250.

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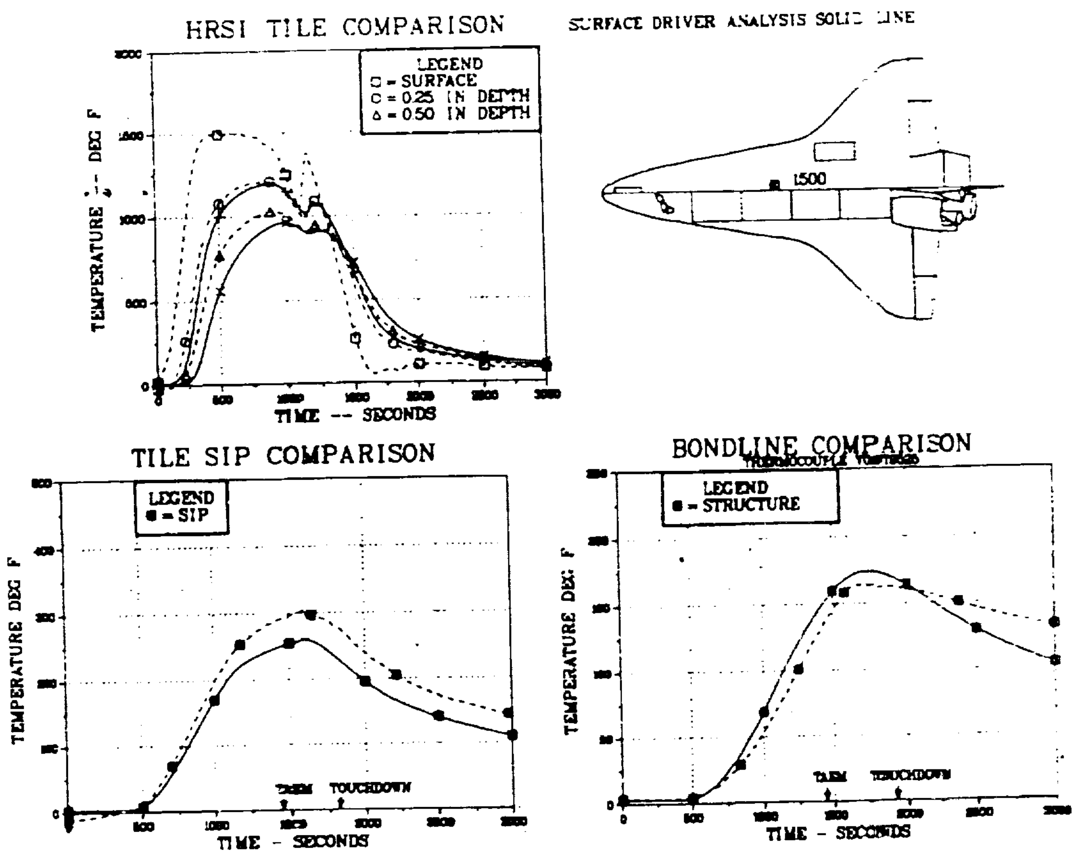

Figure 14.- STS-5 comparison of flight data versus analyses - body point 1500.

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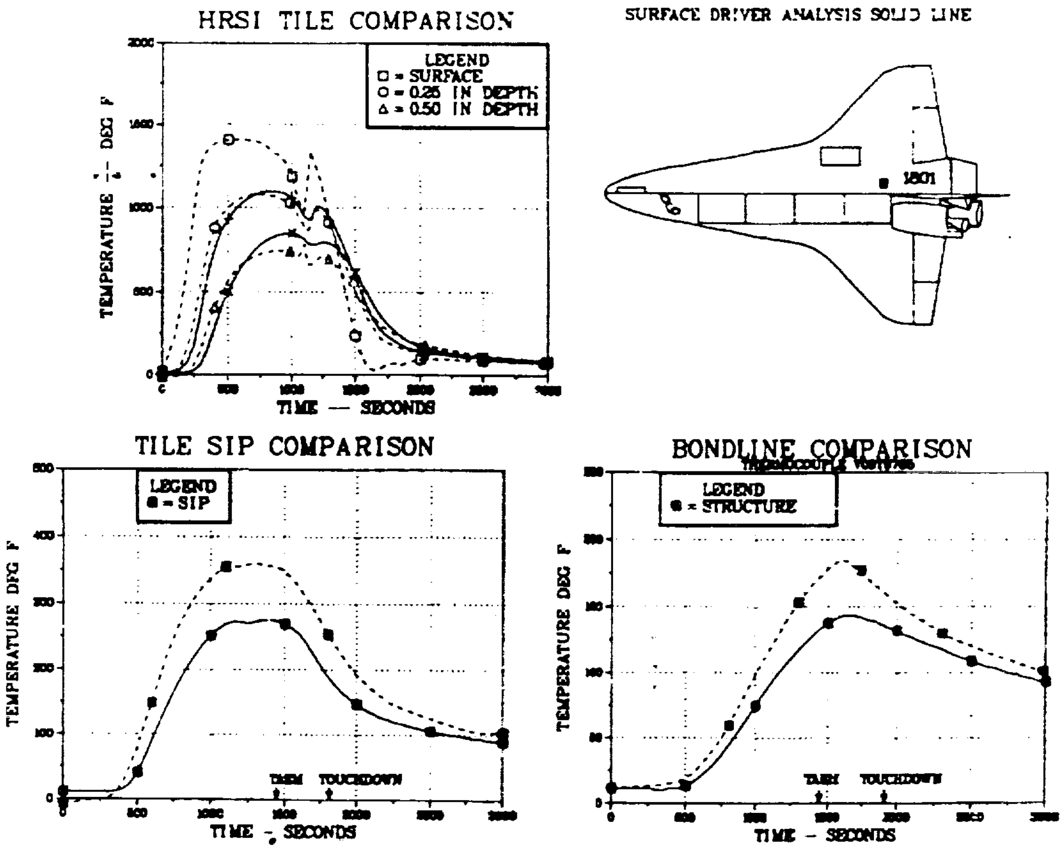

Figure 15.- STS-5 comparison of flight data versus analyses - body point 1801.

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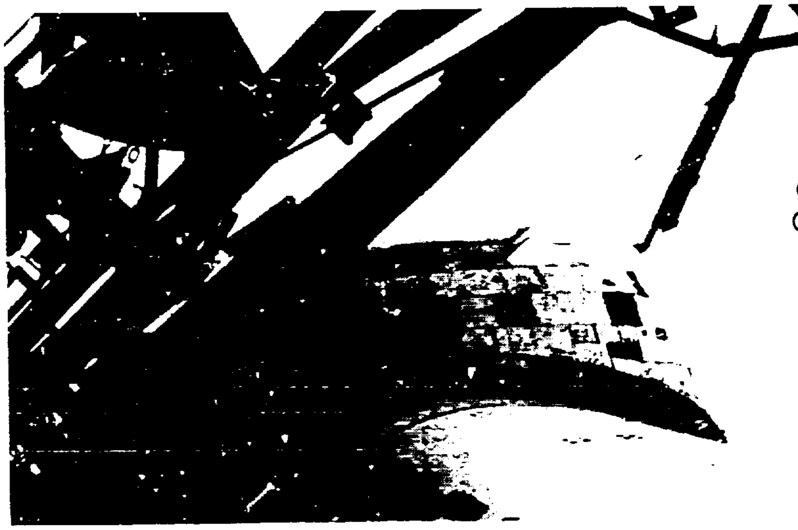

Figure 16.- Loss of diced LRSI tiles on OMS pod - STS-1.

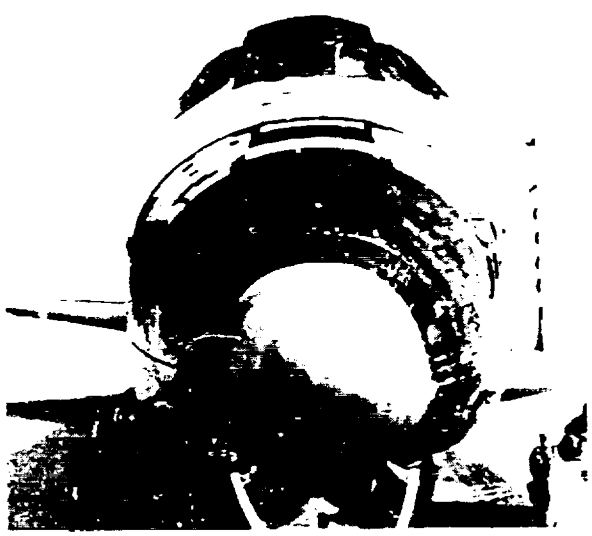

Figure 17.- Loss of nondensified tiles on forward fuselage area - STS-3.

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Figure 18.- Loss of nondensified tiles on upper surface of body flap - STS-3.