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ORBITER CATALYTIC/NONCATALYTIC HEAT TRANSFER AS EVIDENCED BY HEATING TO CONTAMINATED SURFACES ON STS-2 AND STS-3

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SUMMARY

During that portion of Space Shuttle orbiter entry when significant aerodynamic heat transfer occurs, the flow over the vehicle is in chemical nonequilibrium. The parameter which most significantly influences the level of surface heat transfer in such a flow field is the catalytic efficiency of the surface with respect to the recombination of dissociated oxygen atoms. Significant, and instantaneous, changes were observed in the level of heat transfer at several lower-surface centerline locations on STS-2 and STS-3. This phenomenon apparently resulted from a sudden change in the surface catalytic efficiency at these locations due to contamination of the surface by metallic oxides. As a result, data obtained from affected measurements cannot be considered as "benchmark" data with which to attempt to characterize nonequilibrium heat transfer to the orbiter's lower surface centerline.

INTRODUCTION

The design of the thermal protection system (TPS) of the Space Shuttle orbiter was based upon predicted aerothermodynamic environments which were generated assuming that the orbiter flow field was everywhere in chemical equilibrium (ref. 1). Detailed preflight calculations (refs. 2 and 3), however, indicated that significant chemical nonequilibrium would persist over the majority of that portion of orbiter entry when significant aerodynamic heat transfer occurs. The parameter which most significantly influences the level of surface heat transfer in such a flow field is the catalytic efficiency of the TPS surface with respect to the recombination of dissociated oxygen atoms. The catalytic efficiency of the reaction-cured glass (RCG) coating on orbiter TPS tiles was thought to be relatively low based upon arc-tunnel experiment results (ref. 4). Therefore, flight heating rates were expected to be lower than "equilibrium chemistry" predictions as a result of the combination of nonequilibrium chemistry and a non-fully-catalytic TPS surface.

The desire to confirm, in flight, the apparent low catalytic efficiency of the RCG coating and the accompanying benefits of nonequilibrium heat transfer to that surface led to the development of the NASA Ames Research Center's Catalytic Surface Effects (CSE) Experiment (refs. 5 and 6). CSE experiment results were obtained on STS-2, 3, and 5. The STS-2 data (ref. 6) provided graphic evidence that the RCG coating of the orbiter's TPS tiles is indeed

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"noncatalytic." The flight data showed that surface temperatures of the CSE-experiment catalytic-coated tiles were substantially greater than those of the baseline tiles and that, therefore, the surface catalytic efficiency of the baseline tiles is low.

In addition to the CSE experiment, however, an unexpected event occurred during the orbital flight test mission entries which provided further information into the catalytic/noncatalytic nature of orbiter windward-surface heat transfer. This "unplanned experiment" manifested itself in instantaneous, significant changes in measured TPS surface temperatures at affected measurement locations. The phenomenon occurred to varying degrees on both STS-2 and STS-3. It was apparently the result of anomalous deposition of metallic oxides on portions of the lower surface TPS, due to oxidation of upstream acoustic sensor covers (ref. 7). Although occurrence of the phenomenon has been recognized in the literature (refs. 7-10), there has been little analysis of the qualitative information relative to catalytic/noncatalytic heat transfer which is embodied in the resulting data. This paper provides comparisons of the heat transfer to affected measurement locations from mission to mission and to contaminated versus noncontaminated surfaces. Discussion of the implications of these results should aid in assessment of the overall quality of data obtained from these and later flights and corresponding flight-data analyses.

SYMBOLS AND ACRONYMS

CSE	Catalytic Surface Effects
DFI	Development Flight Instrumentation
h	altitude
q	convective heat-transfer rate
q_{ref}	heat-transfer rate to the stagnation point of a 1-foot radius sphere
POPU	push-over/pull-up maneuver
RCG	reaction-cured glass
T	temperature
t	time from entry interface
TPS	thermal protection system
u	velocity
VxxTxxxx	DFI measurement identification number
X/L	nondimensional body length (L = 1295 inches)

α angle of attack

ρ density

FLIGHT DATA

Source

During the orbital flight test missions, the orbiter was equipped with an instrumentation system referred to as the Development Flight Instrumentation (DFI). The DFI was comprised of over 4500 sensors, associated data-handling electronics, and recorder, which provided data to enable post-flight certification of orbiter subsystems design. Included among the DFI were measurements of the aerodynamic surface temperature at 14 locations on the forward fuselage lower surface. These measurements were obtained from thermocouples mounted within the thermal protection system tiles, in thermal contact with the surface coating. (Temperature measurement locations are shown in figure 1, depicted by the planform of the TPS tile which contains the thermocouple.) DFI temperature data were recorded once each second throughout the time period of entry from Earth orbit. The measured surface temperature-time histories were used to determine the surface heat-transfer rates. DFI tape recorder malfunctions on missions STS-1 and STS-4 resulted in the loss of all thermal data during that portion of entry when the vehicle was not in communications contact with the ground. Therefore, no data were obtained at flight Mach numbers above approximately 14 on STS-1 or STS-4. On STS-5, the DFI measurement locations discussed in this paper were coated with the catalytic coating of the Catalytic Surface Effects experiment. Consequently, only data from missions STS-2 and STS-3 are considered herein.

Heat-Transfer Rate Determination

A one-dimensional, transient heat-conduction analysis (ref. 11) was used to determine the convective heating rate to each measurement location. The flight-measured surface temperature data provided a time-dependent boundary condition for the analysis, which assumes an initially uniform temperature throughout the thermal protection system materials. The analysis is a mathematically rigorous simulation of heat conduction within the thermal protection system, and reradiation from its surface, so as to provide a "benchmark" determination of the flight heat-transfer rates.

The reference heating rate used herein is that to the stagnation point of a 1-foot radius sphere in radiation equilibrium at the flight condition. The heat-transfer rate computation was made by the method of reference 12 using the Fay and Riddell (ref. 13) expression for the stagnation-point heat transfer.

Flight Environment Definition

Determination of the vehicle attitude and free-stream flight environment data used herein was accomplished through post-flight reconstruction of the orbiter entry trajectory and definition of the atmosphere along that trajectory at the time of entry. The trajectory reconstruction process (ref. 14) utilizes ground-tracking data and onboard measurements of orbiter inertial attitude, linear and angular accelerations, and angular rates to determine the vehicle's inertial position, velocity, and attitude throughout the entry. Definition of the atmosphere along the trajectory is accomplished (ref. 15) by combining atmospheric profile data obtained from soundings made on the day of entry with atmospheric modeling techniques to infer the free-stream atmospheric properties of pressure, temperature, density,* and winds at the time of entry. The results of the trajectory and atmospheric reconstruction processes are melded together to provide an analytically and physically consistent definition of the free-stream flight environment.

TEMPERATURE "JUMP" ANOMALY

The temperature history measured during STS-2 at the X/L = 0.194 location on the windward centerline (fig. 2) graphically illustrates the temperature "jump" anomaly observed at several locations on the windward centerline on both STS-2 and STS-3. The sudden "jump" in surface temperature was apparently caused by an instantaneous change in the catalytic efficiency of the TPS surface at this location which resulted in increased aerodynamic heat transfer. The change in surface catalytic efficiency apparently resulted from deposition on the surface of oxidation products from upstream, stainless-steel, acoustic sensor covers. Acoustic sensors were located in tiles at X/L = 0.106 and X/L = 0.204 (fig. 1). Post-flight vehicle inspection revealed the oxidation occurrence and deposition of oxidation products downstream of the acoustic sensors. Figure 3 shows the post-flight condition of the acoustic sensor located at X/L = 0.106 (fig. 3(a)), and the trail of contamination left on the downstream TPS surface (fig. 3(b)), after the STS-1 entry. It should be noted that although the surface contamination was observed after STS-1, the potential influence of this contamination on surface heat transfer was not recognized until the temperature "jump" anomaly was observed in the STS-2 data.

Scott and Derry (ref. 7) stated that the oxidation products were iron oxide and nickel oxide. They have postulated that the temperature of the sensor covers reached a value at which they "began to violently react with the oxygen in the flow. The oxide was then carried downstream and was deposited on the tiles. Since iron oxide and nickel oxide are highly catalytic to oxygen and nitrogen recombination, the coating caused increased heating on the contaminated tiles. The oxides may also have catalyzed atom recombination in the gas phase, as well, which would cause an increase in boundary-layer temperature."

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*For STS-2, free-stream density was determined as described. For STS-3, however, in the altitude range from 185,000-250,000 feet, density data were determined using measured orbiter surface pressure data. Measured surface pressures near the orbiter nose were processed using the methods of reference 16 to derive free-stream dynamic pressure information. Density was then inferred using this dynamic pressure data and the velocity from the reconstructed trajectory.

Table I provides a reference summary of the tile surface condition and observed temperature anomaly response at each of the centerline measurement locations on STS-2 and STS-3. On STS-2, the temperature "jump" phenomenon was observed at centerline measurement locations at $0.194 \leq X/L \leq 0.402$. At the most aft of these locations ($X/L = 0.402$), the STS-2 temperature anomaly response was a temperature decrease as opposed to the increase observed at the other locations. This tile was catalytically coated as part of the CSE experiment. If surface contamination had caused a sudden increase in the catalytic efficiency of the TPS surface upstream of this location, as is suggested by the available evidence, a sudden depletion in the number of dissociated oxygen atoms reaching the location of the catalytic-coated tile would result. Therefore, with suddenly fewer oxygen atoms available for recombination, the sudden temperature decrease which was observed would be expected - not due to local surface contamination, but rather to the residual effect of upstream surface contamination. On STS-3, the temperature "jump" was only observed at the $X/L = 0.194$ and $X/L = 0.285$ measurement locations. Why the phenomenon was not observed at other locations is not fully understood, but it is thought to relate to a progressively increasing level of contamination with each flight. The temperature "jump" anomaly was not observed at locations not on the lower surface centerline.

ANALYSIS

STS-2/3 Trajectory Comparison

Before valid comparisons can be made between heat-transfer data for STS-2 and STS-3, one must understand the comparative relationship of the two entry trajectories. Velocity and atmospheric density data for the two entries are shown in figure 4 for the altitude range of interest for this paper. While density levels were similar for the two entries, the STS-3 entry velocity was slightly greater than for STS-2. Because of the higher entry velocity, the orbiter reached a particular flight condition earlier in time on STS-3 than STS-2. Consequently, time from entry interface is not considered to be an appropriate parameter for correlation of data for the two flights.

The reference heating rate (i.e., that to the stagnation point of a 1-foot radius sphere at the flight condition) variation as a function of altitude is shown in figure 5 for both entries. The reference heating rate levels are comparable at a given altitude, with the maximum difference between the STS-2 and STS-3 reference rates being less than 4 percent of the mean. Vehicle angle of attack was nominally constant at 40 degrees on both STS-2 and STS-3 over the altitude range of interest (fig. 5). Because of these relationships, heat-transfer data compared herein will be shown in dimensional form with STS-2/STS-3 comparisons made as functions of altitude.

Non-Contaminated Surfaces

In order to demonstrate the similarity of the heating environments on STS-2 and STS-3, heat transfer data for two locations which were not subject to contamination are shown in figure 6. The first location (fig. 6 (a)) is on the windward centerline at $X/L = 0.093$, just upstream of the more forward acoustic sensor. The second location (fig. 6 (b)) is at X/L = 0.297, but is 51 inches away from the centerline. For these locations, which were not subject to surface contamination, the levels of heat transfer experienced on STS-3 were approximately the same as were experienced on STS-2. (The small differences observed between the STS-2 and STS-3 heating rate levels are of the same magnitude as the uncertainty of the derived heating rates themselves.)

Contaminated Surfaces

On STS-3, the temperature "jump" anomaly was observed at only two measurement locations. At one of these locations, the aerodynamic surface was that of a baseline tile which had experienced previous entry exposures, and potential contamination, on STS-1 and STS-2. At the second location, the aerodynamic surface was that of a virgin tile with no prior entry exposure or possible contamination. This tile was part of the Tile Gap Heating experiment panel (ref. 17) which was replaced prior to each flight. Discussion of heat transfer to contaminated surfaces will focus on these two locations.

Multiple-Exposure Tile

Heat transfer data from the measurement location at X/L = 0.194 for both STS-2 and STS-3 are shown in figure 7. The tile at this location was "original equipment" and, therefore, subject to prior contamination. On STS-2, the occurrence of the contamination event resulted in a 40 percent step increase in heat transfer at this surface location. On STS-3, the increase was only 25 percent, but the underlying heating rate immediately before the contamination event was higher than for STS-2. Comparing the levels of heat transfer between STS-2 and STS-3 after the contamination events (altitude < 238,000 ft), the STS-3 heating rate level was approximately 18 percent greater than the STS-2 level. This implies a mission-to-mission progressive contamination of the TPS surface with an attendant increase in the surface catalytic efficiency at this location. It is also interesting to note that the STS-2 post-contamination data and STS-3 pre-contamination data (ostensibly equal levels of contamination) correlate well over the entire altitude range considered (fig. 8). It is unfortunate that there are no data from STS-4 to add to this comparison.

Virgin Tile

Heat-transfer data for the tile with no prior exposure history, X/L = 0.285, is shown in figure 9. On STS-2, the heat transfer increase resulting from the contamination event was 40 percent. On STS-3, the step increase was only about 17 percent, but the underlying heating rate immediately before the contamination event was higher than for STS-2. Note that after the contamination event (h < 238,000 ft), the heating rates to this surface were the same on both STS-2 and STS-3. The tile surface at this location was not subject to progressive contamination, as was the multi-mission tile, but was subject to single event contamination on two different entries. Equal levels of contamination would be expected on each entry and, therefore, equal levels of heat transfer following contamination, as are shown in figure 9.

Previously-Catalytic Surface

A somewhat different catalytic surface heating phenomenon has been observed in the flight data from the measurement at X/L = 0.166. The tile containing this measurement was coated on STS-2 with the high-catalytic-efficiency coating of the CSE experiment. Prior to STS-3, the tile was ostensibly cleaned of the coating so as to return the surface to the uncoated "baseline" condition. Data obtained from this measurement on STS-3, however, indicated that the tile surface, after cleaning, remained substantially more catalytic than baseline tile surfaces. This is clearly illustrated in figure 10 where the STS-3 data from this measurement are compared with data from those measurement locations just upstream and downstream of this tile. If the surface catalytic efficiencies at each of these locations were the same, the data from the X/L = 0.166 location would be expected to fall between the values obtained at the other two locations. However, the heat transfer rates observed at this location are always equal to or greater than those observed even at the more upstream location (X/L = 0.140), over the altitude range considered. Why the heating rate to the X/L = 0.166 location "peaks" as it does, at approximately 247,000 feet altitude, is not fully understood. However nonequilibrium viscous shock layer computations have indicated that maximum nonequilibrium effects on surface heat transfer would be expected to occur in this altitude range (refs. 18 and 9).

CONCLUSIONS

The foregoing discussion of the heat transfer results from STS-2 and STS-3 provides strong evidence that portions of the TPS surface on the lower centerline of the orbiter's forward fuselage have been contaminated with materials which have altered the catalytic efficiency of the TPS surface. Specific sources of contamination were the acoustic sensors and the catalytic overcoat of the CSE experiment. As a result, data obtained from affected measurements cannot be considered as "benchmark" data with which to attempt to characterize nonequilibrium heat transfer to the orbiter's lower surface centerline with baseline TPS. Even the first high altitude, high Mach number data obtained on STS-2 are probably biased by contamination which was experienced on STS-1.

Experience with the tile which was catalytically coated on STS-2 and "cleaned" prior to STS-3 indicates that once the coating material is applied and exposed to the entry environment, the catalytic efficiency of that tile surface is apparently permanently altered. The majority of the instrumented tiles on the lower surface centerline were catalytically coated on STS-4 and STS-5. It is, therefore, presumed that the catalytic efficiency of these tile surfaces has been irreversably altered.

Alas, during the orbital flight test missions of the orbiter, not one set of data was obtained for the lower surface centerline with a clean TPS surface of nominal baseline catalytic efficiency. Since the lower surface centerline is the one area which can be adequately modeled by nonequilibrium flow-field and boundary-layer codes, the lack of flight data on a surface of known and uniform thermochemical properties is a significant obstacle to any effort to determine catalytic efficiencies and surface recombination rates using flight data as a "benchmark."

It is proposed that serious consideration be given to replacement of all lower surface centerline tiles, at some future date, with new "virgin" tiles, and that substantially more of these tiles be instrumented. Such a retrofit would also eliminate the acoustic sensors and any other potential contamination source. Future flights with a "clean" lower surface centerline would provide the "benchmark" flight data required to characterize the orbiter's nonequilibrium heating environment—data which were anticipated from the orbital flight tests, but apparently never obtained.

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TABLE I

MEASUREMENT	X/L	STS-2		STS-3	
		TILE SURFACE CONDITION	TEMPERATURE ANOMALY RESPONSE	TILE SURFACE CONDITION	TEMPERATURE ANOMALY RESPONSE
V09T9341	0.025				
V07T9452	.098				
ACOUSTIC	.106				
V07T9462	.140				
V07T9463	.166	Catalytic			
V07T9464	.194		Discontinuous increase		Discontinuous increase
ACOUSTIC	.204				
V09T9381	.255		Discontinuous increase		
V09T9421	.285	Virgin tile	Discontinuous increase	Virgin tile	Discontinuous increase
V07T9468	.297		Discontinuous increase	Catalytic	
V07T9471	.402	Catalytic	Discontinuous decrease	Catalytic	
V09T9521	.497				

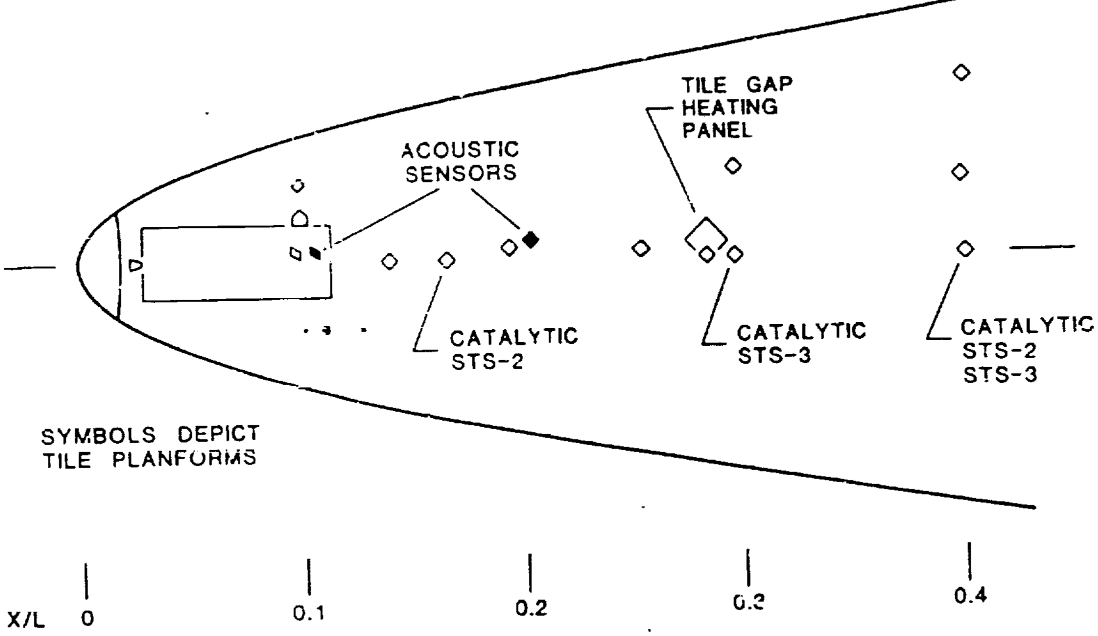


Figure 1.- Forward fuselage lower surface temperature measurements.

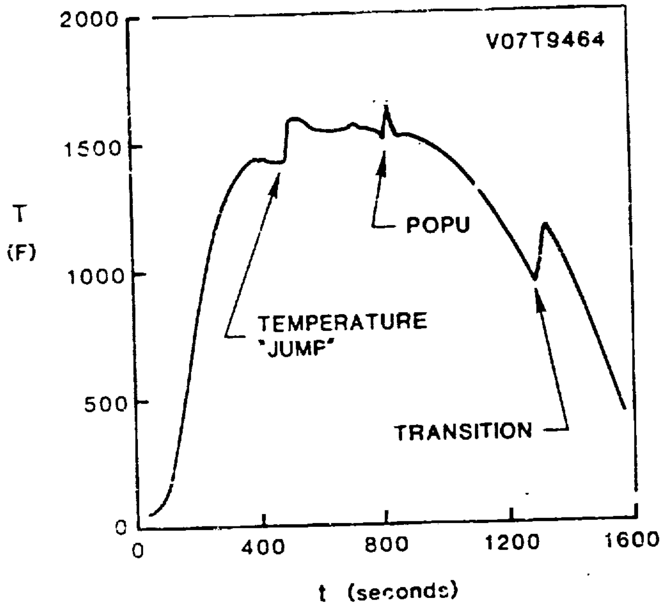
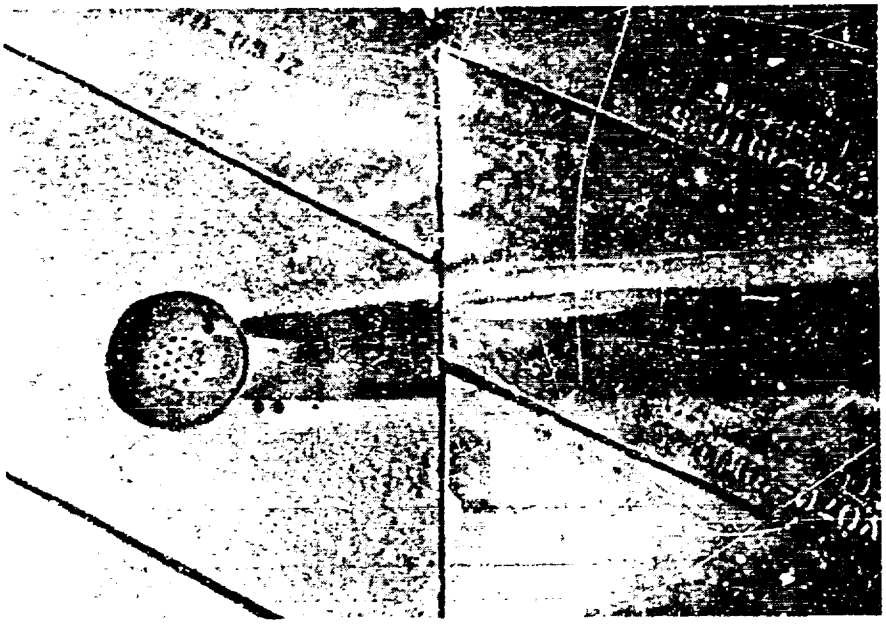
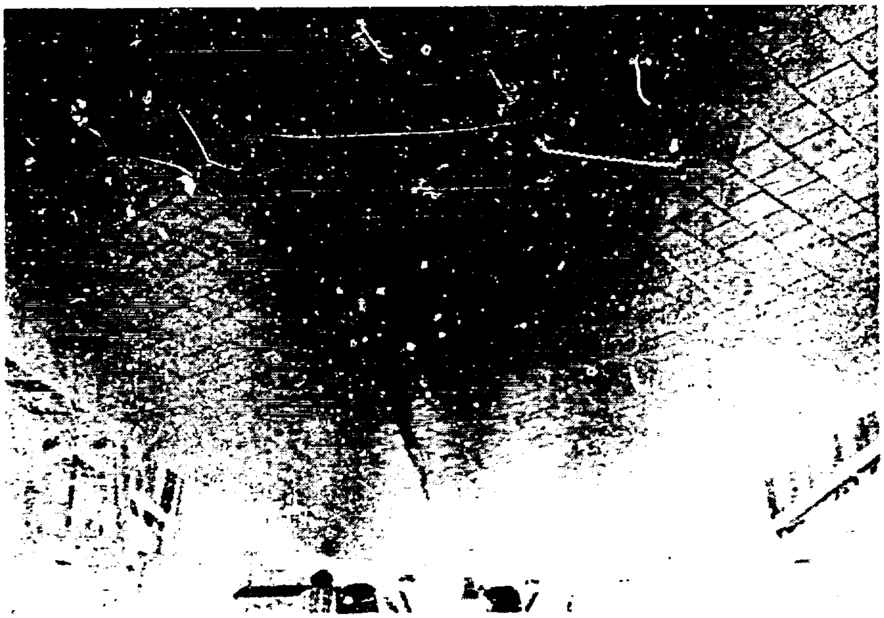


Figure 2.- STS-2 temperature-time history at X/L = 0.194.



(a) Acoustic sensor at X/L = 0.106.



(b) Orbiter lower surface looking forward.

Figure 3.- STS-1 TPS surface [illegible]ination emanating from acoustic s[illegible]

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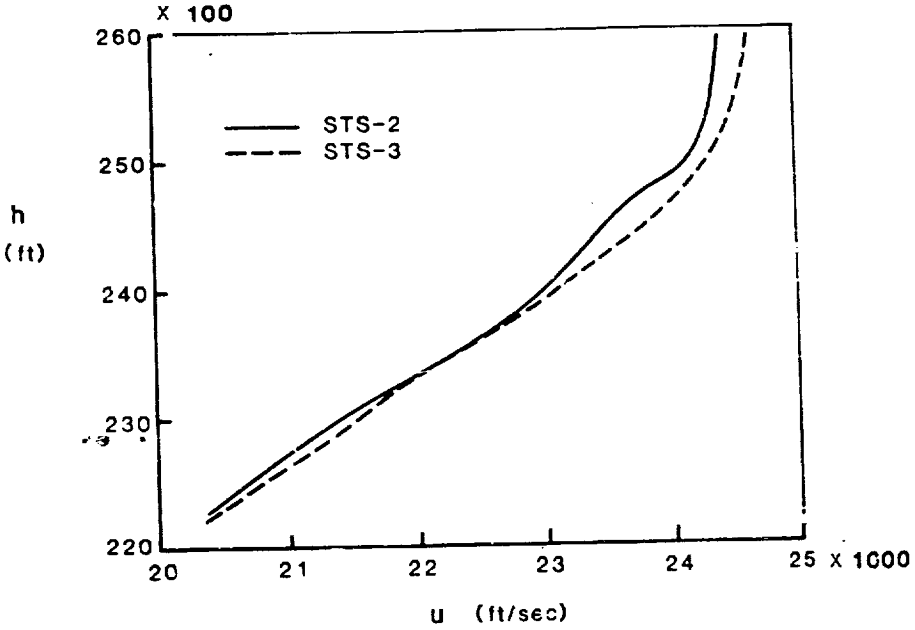
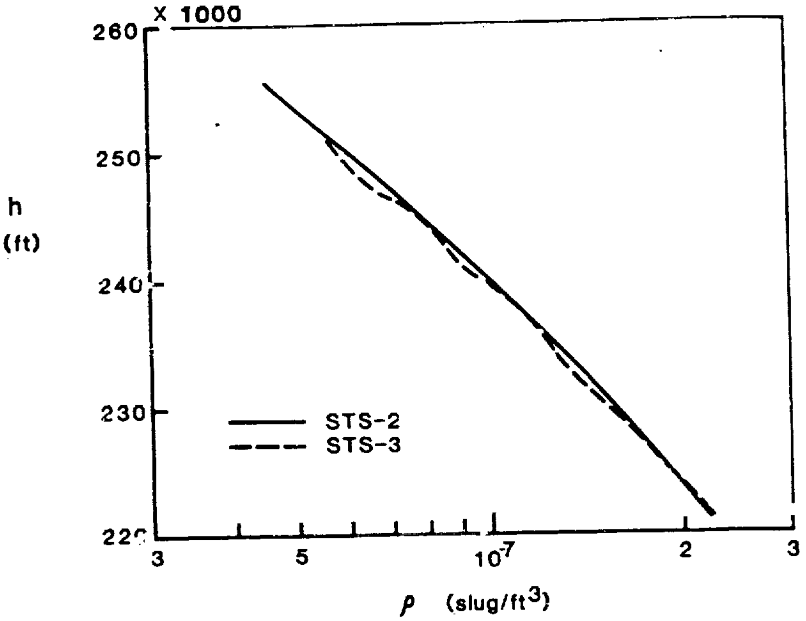


(a) Velocity-altitude.



(b) Density-altitude.

Figure 4.- STS-2/STS-3 entry trajectory comparison.

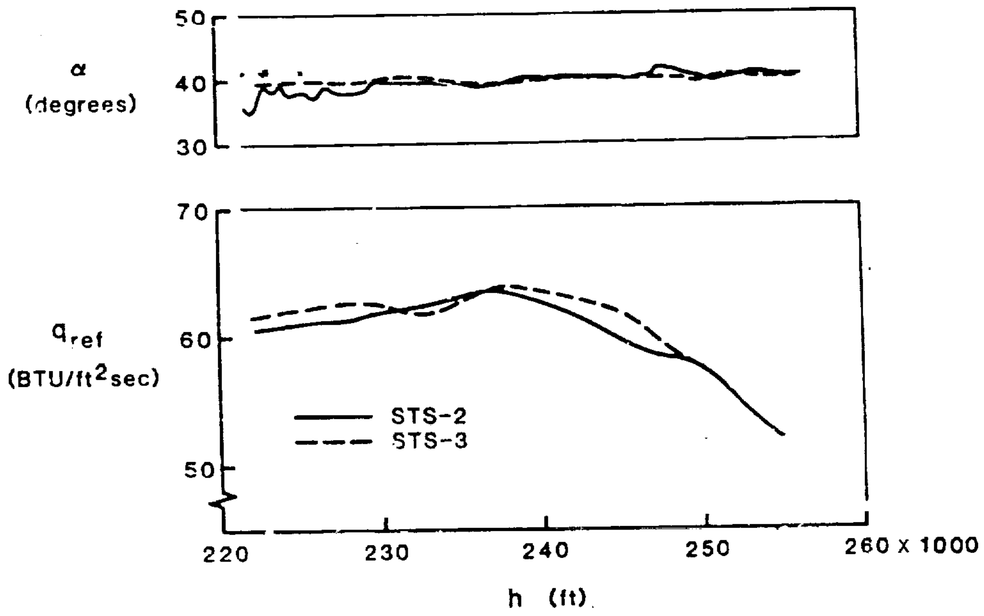
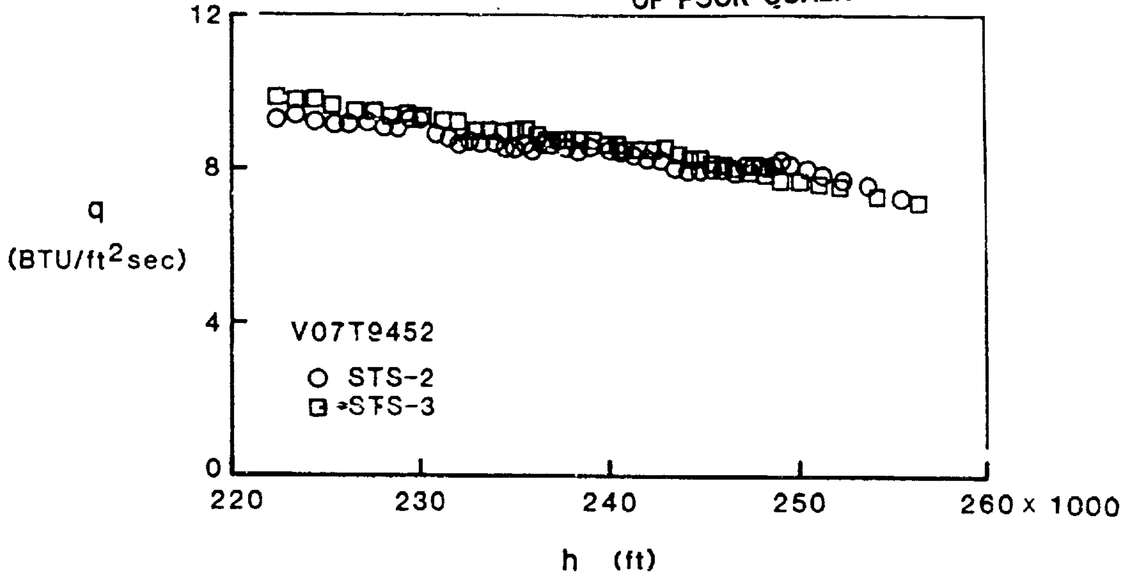
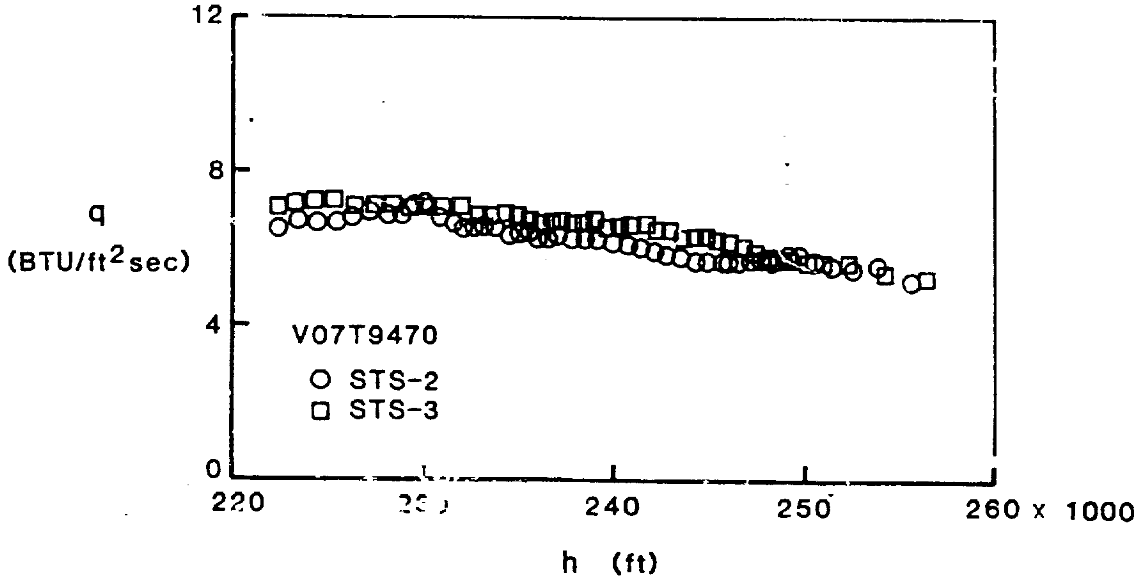


Figure 5.- STS-2/STS-3 angle of attack and reference heating rate comparisons.



(a) X/L = 0.098.



(b) X/L = 0.297, off centerline.

Figure 6.- Heat transfer to noncontaminated surfaces.

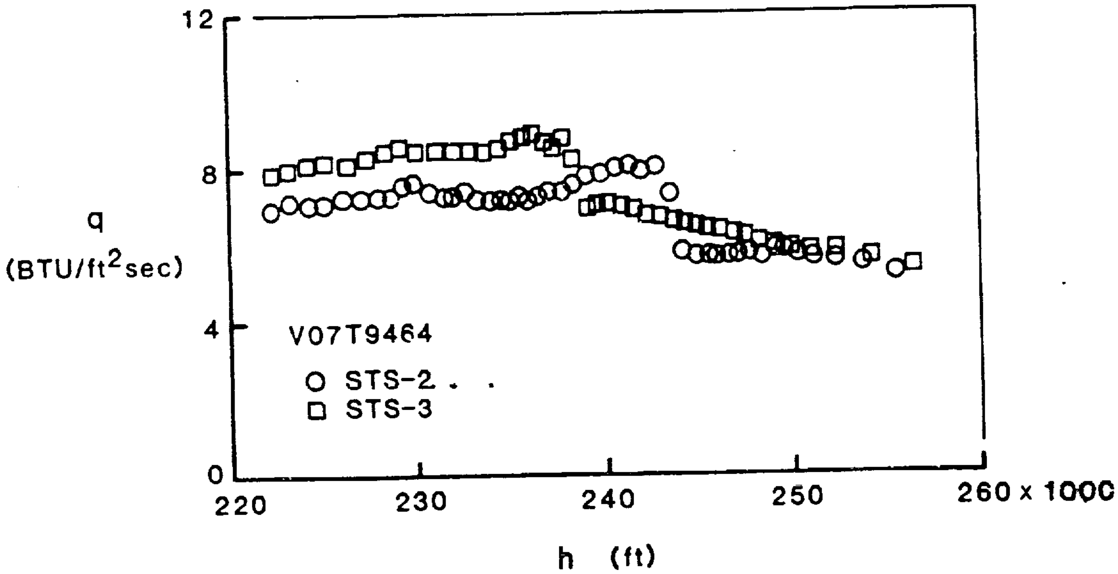


Figure 7.- Heat transfer to "multiple-exposure" tile, X/L = 0.194.

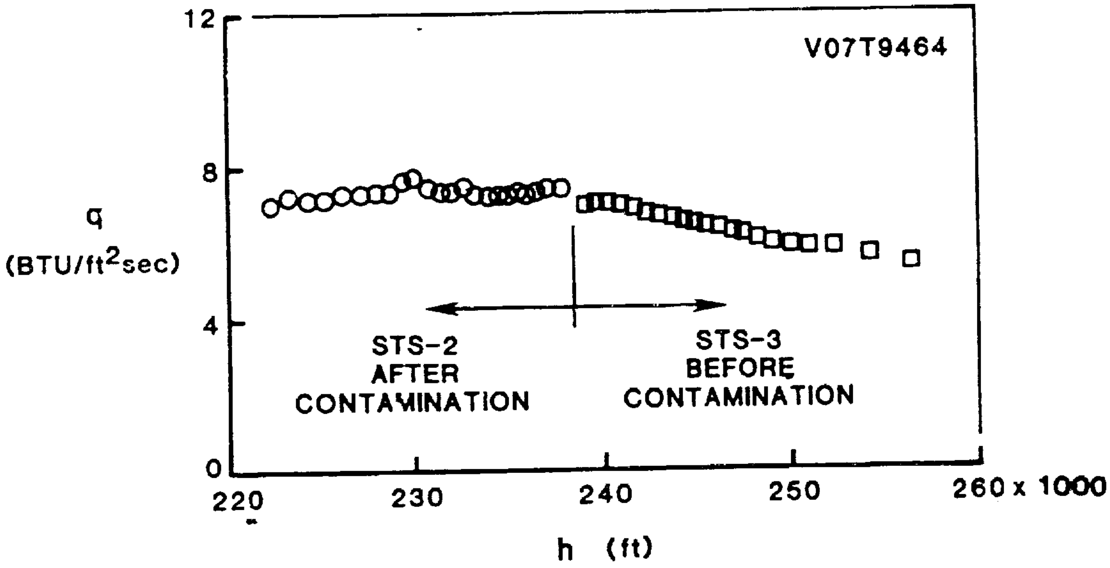


Figure 8.- Heat transfer to "multiple-exposure" tile, X/L = 0.194.

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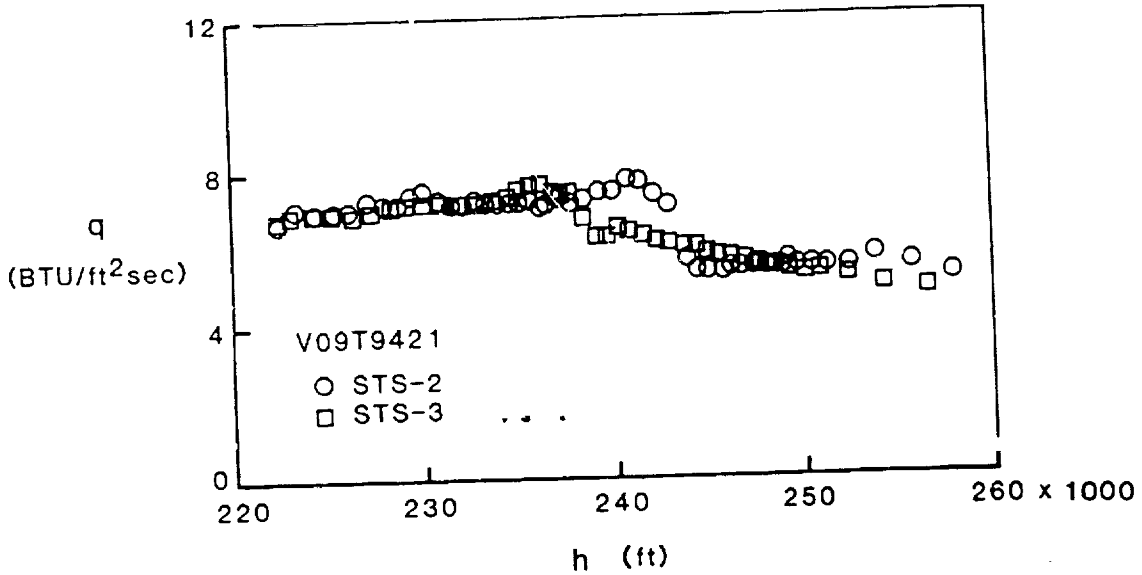

Figure 9.- Heat transfer to "virgin" tile, X/L = 0.285.

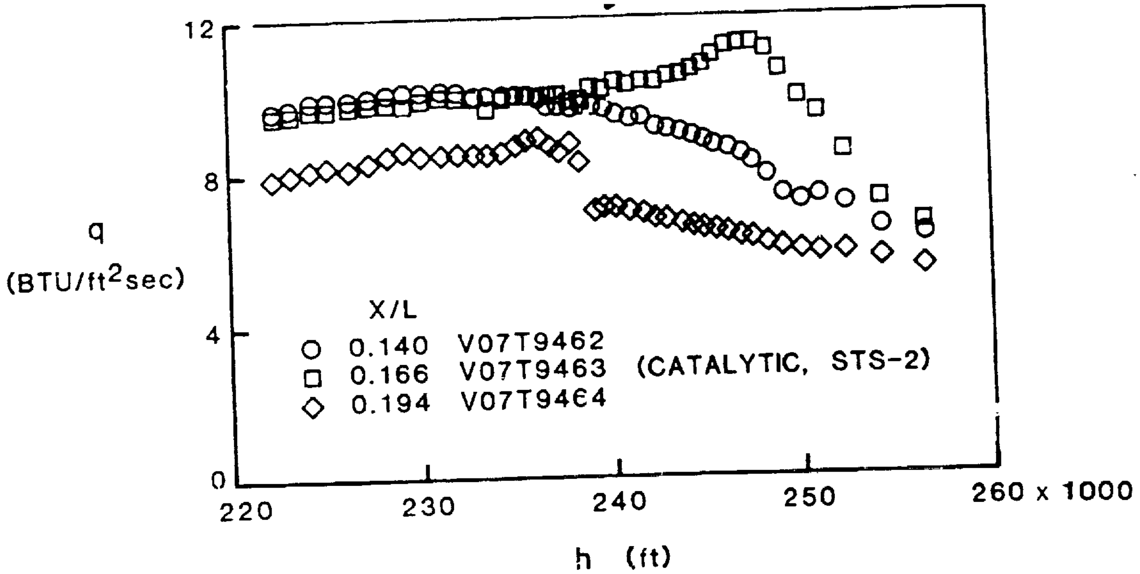

Figure 10.- Heat transfer to "previously-catalytic" tile, X/L = 0.166.