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FILLER BAR HEATING DUE TO STEPPED TILES IN THE SHUTTLE ORBITER THERMAL PROTECTION SYSTEM

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SUMMARY

An analytical study has been performed to investigate the excessive heating in the tile-to-tile gaps of the Shuttle Orbiter Thermal Protection System (TPS) due to stepped tiles. The excessive heating was evidenced by visible discoloration and charring of the filler bar and strain isolation pad (SIP) that is used in the attachment of tiles to the aluminum substrate. Two tile locations on the Shuttle orbiter were considered, one on the lower surface of the fuselage and one on the lower surface of the wing. The gap heating analysis involved the calculation of external and internal gas pressures and temperatures, internal mass flow rates, and the transient thermal response of the thermal protection system. The results of the analysis are presented for the fuselage and wing location for several step heights. The results of a study to determine the effectiveness of a half-height ceramic fiber gap filler in preventing hot gas flow in the tile gaps are also presented.

INTRODUCTION

The Shuttle Orbiter Vehicle 102 (Columbia) has successfully flown five orbital missions. The Thermal Protection System (TPS) on the orbiter exterior has performed satisfactorily although damage has been observed on random individual tiles after each flight. One of the causes for damage to the TPS has been vertical and lateral relative movement between adjacent tiles that do not have gap filler. This relative movement can cause forward facing steps on the TPS aerodynamic surface and large gaps between the tiles. The combination of forward facing steps and large tile-to-tile gaps has caused higher than expected heating within the gaps during atmospheric entry at random locations on the lower surface of the orbiter resulting in damage to the filler material and the strain isolation pad (SIP). The heat damage has been severe enough in some instances to require tile removal in order to replace the filler material and SIP. Filler material damage was observed on the lower fuselage and the lower surfaces of both wings of the orbiter. These regions are geometrically flat regions so that aerodynamic pressure gradients on the TPS are essentially zero. Tile-to-tile gap fillers were not used in these regions for this reason.

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An analytical study was conducted to determine the magnitude of tile steps and gaps that would cause the observed filler bar damage. This paper describes the techniques used to define the conditions under which damage to the filler bar would occur. There is also a discussion of a possible fix to the problem.

SYMBOLS

A_c	cross sectional area for flow
B	width of flow path
G	conductance for laminar flow between parallel plates
G_1	conductance of gap with full gap filler
G_2	conductance of gap with half-height gap filler
h	tile step height
k	thermal conductivity
K_p	permeability constant
L_t	tile thickness
$\dot{m}$	mass flow rate
M	Mach number
P	pressure
$\dot{q}$	conduction heat flux
Re_c	Reynolds number for base pressure correlation
s	straight line length between points
T	temperature
w	tile-to-tile gap width
X,Y	Shuttle orbiter coordinates
ΔX	longitudinal coordinate measured in the downstream direction from the point of separation
ΔX_{ff}	longitudinal coordinate measured in the upstream direction from a forward facing step

δ	velocity boundary layer thickness
δ^*	boundary layer displacement thickness
δ_{eff}	1.5 δ^* for turbulent flow, δ for laminar flow
Λ	sweep angle of a tile with respect to the local flow
μ	viscosity coefficient
ρ	density

PROBLEM DESCRIPTION

The TPS on the lower fuselage and lower surfaces of the wings (figure 1) consists of silica foam tiles typically 6 x 6 inches square and of variable thickness depending on their location on the orbiter. There is a glass coating containing black pigment on the exterior of the tile to increase the radiative properties of the surface. Radiating heat from the tile surface during entry is a key consideration in the thermal design of the TPS. The tiles are bonded to the aluminum skin of the orbiter through a strain isolation pad (SIP). The SIP is a nylon fiber material that is used to absorb relative movement between the brittle silica tiles and the aluminum substrate. The tiles have gaps between them to allow for differential thermal expansion between the tiles and substrate. The nylon fiber filler bar is directly beneath the tile-to-tile gaps. There is a silicone rubber membrane on the top surface of the filler bar to prevent hot gases from flowing under the tiles. The filler bar is bonded to the aluminum skin but not to the bottom of the tiles. This filler bar material sustained damage on all flights of the Columbia, the first Shuttle.

Post-flight measurements, taken after the first flight around the tiles with damaged filler bar, are shown in table 1. Tile-to-tile steps varied from -0.1 inch to +0.12 inch and tile gaps varied from almost complete closure (0.01 inch) to an opening of 0.13 inch. NASA Johnson Space Flight Center categorized the degree of damage to the filler bar by performing arc jet tests on a TPS panel and duplicating the varying degrees of observed damage. Thermocouples were embedded in the filler bar to record temperatures for each category of damage. The threshold temperature to cause filler bar damage was 970°F causing the RTV rubber membrane to discolor. Temperature exposures above 1375°F caused both the RTV and nylon fiber material to char.

The probable cause of damage to the filler bar is shown in figure 2. A tile with a forward facing step causes a local pressure disturbance in the external boundary layer. The flow tends to stagnate on the forward face directly over the tile-to-tile gap. Similarly, the aft facing step creates a low pressure region as the flow leaves the surface of the stepped tile and reattaches downstream. This combination of pressures around a stepped tile causes flow in the tile gaps that would not exist if all tiles were at the same height. The objective of the analytical study was to define the conditions under which a stepped tile could result in damage to the filler bar. In order to define these conditions, five major phases of study were required:

(1) Definition of the local freestream conditions on the lower surface of the wing and fuselage

(2) Development of a technique for predicting the distribution and magnitude of the pressure disturbance caused by a stepped tile

(3) Predicting the temperature of the gases which enter the tile-to-tile gap from the external boundary layer as a result of the stepped tile

(4) Predicting the pressure distribution around and under the tile and the mass flow rates in the tile gap as a result of the pressure disturbance

(5) Determining the temperature response in the tile gap and in particular the temperature on the filler bar caused by flow in the gaps

ANALYSIS

Two locations, one on the lower surface of the fuselage and one on the lower surface of the left wing, were selected for analysis from the regions where damaged filler bar was observed (figure 3). The location on the fuselage was selected because local flow conditions during entry can be accurately predicted for this position, flight measurements of pressure and temperature are available, and the boundary layer thickness will be large since the point is about 40 feet from the nose of the orbiter. The wing location was selected for the same reasons, except in this case the boundary layer will be relatively thin since the point is about 8 feet aft of the local leading edge. These are 6 inch x 6 inch tiles with thicknesses of 1.41 inches at the fuselage location and 2.25 inches at the wing location.

The pressure and other thermodynamic properties at the edge of the boundary layer at the fuselage location were calculated using a tangent-cone approximation where the half angle of the cone is equal to the local flow deflection angle, (i.e., the local body deflection angle plus the angle of attack). The real gas, axisymmetric, flow-field solution over a cone was obtained using a time-asymptotic numerical procedure with equilibrium thermodynamic properties obtained from reference 1. The tangent-cone approximation has been shown to yield accurate predictions of the local flow on the windward surface of Shuttle-like configurations (reference 2). Local flow conditions on the wing lower surface were calculated assuming two dimensional inviscid flow. The boundary layer calculations on the fuselage were made using a "local infinite swept cylinder" analysis (reference 3) and on the wing using two-dimensional "strip theory."

Pressure Disturbances

The characteristic shape of the pressure disturbance caused by a forward facing step in supersonic flow is shown in figure 4. The step height needed to cause this disturbance is equal to or greater than the boundary layer thickness for laminar flow and equal to or greater than 1.5 times the displacement thickness for turbulent flow. The step causes the boundary layer to separate locally from the body forward of the step. In addition, an oblique shock is formed at the point of separation. The pressure behind the shock is called the plateau pressure, $P_{plateau}$, in figure 4. There is a final peak pressure at the face of the step as the flow stagnates. The figure is a plot of $P_{plateau}/P_{local}$ versus Mach number from test data obtained in the LaRC Unitary Plan Wind Tunnel and experimental results reported in the literature (references 4, 5, and 6). The data are directly applicable to the lower surface of the orbiter since the local Mach number behind the bow shock ranges from 2.5 - 3.75 during the high aerodynamic heating period of entry. The equation for a straight line correlates the data very well as is shown in the figure.

Boundary layer thicknesses varied from 0.87 inch to 4.0 inches at the fuselage location and 0.54 to 1.54 inches at the wing location. Tile step heights considered in the analyses were 0.12 inch maximum in accordance with measured tile steps after the first flight. Therefore, forward facing steps in the tiles were deeply submerged in the boundary layer and do not cause the severe pressure disturbances shown in figure 4. Figure 5 shows experimental data for pressure distribution versus separation distance for various step heights. The face of the step is at $\Delta X_{ff}/\delta^* = 0$ in the figure. The shaded symbols indicate data that is in the range of step height-to-displacement thickness ratios that apply for the filler bar analysis. A significant feature of the plots in figure 5 is the similarity of the curves as step height is decreased. The characteristic shape of the pressure distribution for a large forward facing step ($h/\delta^* = 1.5$) can be used to obtain the pressure distribution for a smaller step height by using the lower portion of the curve starting at the point of separation and scaling the peak pressures as a function of h/δ^*. A correlation technique was developed to obtain pressure disturbance distributions for small step heights at various Mach numbers between 2.35 - 3.85 based on the experimental data previously referenced. Figure 6 shows the result of the correlation technique being applied at M = 3.85. The pressure distribution curves are plotted as a function of the nondimensionalized separation distance. The separation point is at $\Delta X/\delta^* = 0$. The lower dashed curve is the correlated pressure curve for the step height that is 1.5 times the displacement thickness of the turbulent boundary layer ($\delta_{eff} = 1.5\ \delta^*$). It has the characteristic shape of a pressure disturbance that has an oblique shock at the separation point shown previously in figure 4. The top dashed curve envelopes the peak pressures for various step heights. For the filler bar analyses, the pressure disturbances were obtained by using the lower dashed curve from the point of separation to an appropriate point and then fairing a distribution to the enveloping curve for the step height of interest. Details of the development of the correlation technique can be found in reference 7.

The effect of sweep angle on the pressure distribution in front of a forward facing step was taken into account using data from reference 8 (figure 7). The forward face of a stepped tile was assumed to be swept 45° with respect to the local flow. Base pressure predictions on the aft facing steps were based on data from reference 9 (figure 8). The exponent, n, in the definition of characteristic length for the Reynolds number was empirically determined to be 0.9 in the reference.

Flow Model

With the pressure disturbances around the top of a stepped tile defined, pressure distributions in the tile gaps, in the SIP and filler bar, and within the silica foam tile can be calculated along with the resulting mass flow rates. Figure 9 is a schematic of a 9-tile array flow model that was developed to analyze the flow around a stepped tile (Tile 9 in figure 9). The tile gaps were modeled as flow passages around the tiles. Boundary conditions at the top of tiles were the calculated pressure disturbances around the stepped tile and a constant pressure, P_{local}, around the other tiles in the array to simulate the zero aerodynamic pressure gradient assumption. Lateral movement of the stepped tile caused by the pressure differences around it were simulated in the flow model because the SIP material is very flexible and allows tile movement. The position of the remainder of the tiles in the array was held constant. Figure 10 shows further detail that was incorporated into the flow model. View A in the figure shows flow passages near the filler bar that were modeled. The flow passages include flow in and out of the bottom of the tile where it is not bonded to the SIP, flow between the tile and filler bar, and flow in and out of the SIP. Flow through the fibrous material of the filler bar was also considered.

The equation that describes flow through porous media,

$$\dot{m} = - \frac{K_p \rho A_c}{\mu} \frac{dP}{ds} \tag{1}$$

is analogous to the steady state heat conduction equation

$$\dot{q} = - k A_c \frac{dT}{ds} \tag{2}$$

The flow in the tile gaps can be described as flow between parallel walls. Mass flow rates between parallel walls for laminar incompressible flow (calculated Reynolds numbers in the tile gaps indicate the flow is laminar to transitional) can be obtained from

$$\dot{m} = - \frac{1}{12} \frac{\rho w^2 A_c}{\mu} \frac{dP}{ds} \tag{3}$$

This equation is also analogous to the equation for steady state heat transfer. By using these analogies, the Martin Interactive Thermal Analyzer System (MITAS) (a general purpose finite difference heat transfer computer program) was used to obtain the pressure and flow distribution around the stepped tile. The flow model, originally developed for a tile loads analysis using ascent conditions, was modified during the study to account for compressibility effects in the tile gap flow. This modification was necessary because pressure differences calculated around the stepped tile were large enough to cause compressible flow. The compressible flow in the tile gaps was modeled assuming internal flow of an ideal gas with constant cross-sectional area and frictional effects (Fanno line flow). Complete details of the modified flow model can be found in reference 7.

Thermal Model

A thermal model representing the region around a stepped tile was developed to determine temperature response to hot gas flow in the tile gaps. The region modeled is shown in figure 11. The model included portions of the two tiles on each side of the gap and the filler bar, SIP, and aluminum substrate at the base of the tiles. It was chosen because the mass flow rates in the tile gap are highest at the corner of the tile where the pressure distribution goes from a high pressure region on the forward face to the low pressure region on the aft face of the stepped tile. The thermal model was limited to this region of the stepped tile to keep the model size within the capacity of MITAS. It was assumed that the temperature of the gas entering the modeled region in the horizontal direction was equal to the temperature of the gas in the gap in the center of the model at the same depth from the surface. This assumption was made because the flow down the gap is much larger than the flow entering the gap in the horizontal direction. The inlet temperature of the gas that entered the tile gap in the vertical direction was assumed to be the integrated average stagnation temperature of the boundary layer air from the tile surface to a point in the boundary layer equal to the tile step height. Convection, conduction, and radiation on the tile sidewalls and top surface were accounted for in the analysis. An energy balance was also maintained on the gas as it flowed through the tile gap.

ANALYSIS RESULTS

Figure 12 is an example of the results from the pressure disturbance calculations. The zero point for atmospheric entry time is taken to be the time at which the orbiter reaches 400,000 feet altitude during entry. Pressure and flow calculations were made at discrete time points with freestream conditions held constant. Flow data for the discrete time points was used in the transient temperature calculations over corresponding time intervals. The curves are terminated at the time when maximum filler bar temperature occurs. The maximum pressure difference across a 0.1 inch stepped tile at the fuselage location was approximately 0.33 psi. Figure 13 is an example of the results obtained from the transient thermal analysis. The result is for a 0.1 inch stepped tile at the fuselage location. The filler bar temperature peaks at 1470°F. It occurs after boundary layer transition (transition is indicated by the rapid rise in inlet gas temperature at 1250 seconds) and after the tile surface temperature has begun to fall. Table 2 shows a summary of peak filler bar temperature results for the fuselage location. Two different tile step heights (0.04 inch and 0.1 inch) were held constant and the tile gap width was allowed to vary. The maximum step size (0.03 inch) and maximum gap width (0.065 inch) that are acceptable during tile installation are also indicated on the figure. Extrapolation of the calculated results to these maximum installation tolerances indicates damage to the filler bar would not occur or at least would be minimized if the tile step height and gap width could be held within the tolerances. Table 3 is a summary of the peak filler bar temperature results at the wing location. Only one gap width (.05 inch) was analyzed. These results also indicate filler bar damage can be minimized by maintaining tile steps and gaps within the specified installation tolerances.

POTENTIAL SOLUTION USING GAP FILLERS

As shown in the analysis, filler bar charring is caused by the flow of hot gases in the tile-to-tile gaps. The rate of hot gas flow in this gap depends on the width of the gap and the size of the forward or rearward facing step at the heated surface. It follows that the filler bar charring problem can be solved by controlling the steps and gaps to within acceptable limits. Since control of steps and gaps in the TPS has been difficult, consideration should be given to installing additional tile gap fillers to reduce hot gas flow.

The suggested solution to the filler bar charring problem is to install gap fillers at all locations where filler bar charring is a problem. The suggested gap filler is different from the gap fillers which have been used previously on the Shuttle orbiter. A sketch of the gap filler design concept is shown in figure 14. The ceramic fiber gap filler would extend up to the height in the gap where the maximum gas temperature and loading due to hot gas flow are within the capability of the gap filler material. The gap filler could be bonded on one side to the tile using a high temperature bonding material (colloidal silica could be used) or it could be bonded at the bottom to the tile or the filler bar using a lower temperature bonding material (RTV could be used). The gap filler would be compressed on installation so that it would remain in contact with the tile side wall when the tiles shift under load. The black glass coating (this coating is 0.02 inches thick with a density of 104 lbm/ft.^{3}) could be left off of the tile side wall where the side wall is covered by the gap filler yielding a net weight reduction. The black coating would be maintained in the upper part of the gap. One of the design requirements for the Shuttle orbiter is a cold soak condition. The cold soak causes the tile-to-tile gap to close so that a gap filler in these gaps will load the tiles. These cold soak loads could be reduced if necessary by cutting out the lower part of the tile to accommodate a thicker gap filler with a nominal gap still maintained in the upper part of the gap as shown in figure 14.

The thermal performance of a half-height gap filler made of ceramic fiber blanket material was estimated by analysis. The material chosen for this gap filler analysis has a density of 6 lbm/ft^3. The permeability used in the analysis was 3.66×10^{-10} square feet as measured for a pressure of 142 psf (pounds per square foot) and a pressure gradient of 1114 psf per foot. (See table 4 for test results.) This gap filler material has a temperature capability of 2600°F. The adjustment to the model to represent the gap filler was to set the tile-to-tile gap such that the flow resistance of the open gap is equivalent to the flow resistance of an 0.05-inch gap with a half-height ceramic fiber gap filler installed. Based on the gap filler permeability of 3.66×10^{-10} square feet and a gap filler installed in the entire gap the equivalent open gap width is 0.00316 inches:

$$G_1 = G \tag{4}$$

$$\frac{K_p \rho w_{gf} B}{\mu L_t} = \frac{1}{12} \frac{\rho w_{pp}^3 B}{\mu L_t} \tag{5}$$

$$w_{pp} = [12 K w_{gf}]^{1/3} = 0.00316 \text{ inches} \tag{6}$$

The equivalent gap width for the case of a half-height gap is approximated by comparison of flow down the gap:

$$G_2 = G \tag{7}$$

$$\frac{K_p \rho w_{gf} B}{\mu (L_t/2)} = \frac{1}{12} \frac{\rho w_{pp}^3 B}{\mu L_t} \tag{8}$$

$$w_{pp} = [24 K w_{gf}]^{1/3} = 0.00398 \text{ inches} \tag{9}$$

The thermal model was run with an initial gap width of 0.004 inches to represent this half-height gap filler being installed in the 0.05-inch tile-to-tile gap. The wing location with an 0.06-inch tile-to-tile step was chosen for the gap filler analysis. The pressure boundary conditions are the same as for the analysis without the gap filler and are given in figure 15. The temperature results of the gap filler analysis are given in figure 16. The results show that the addition of a half-height ceramic fiber gap filler protected the filler bar such that charring would not occur. The maximum filler bar membrane temperature calculated was only 450°F while 970°F is required to start the charring process. The calculated filler bar temperature for the same conditions and

0.05-inch gap without gap filler was 1747°F. The half-height ceramic fiber gap filler reduced the peak filler bar temperature by 1297°F.

CONCLUSION

An analysis of the entry heating that occurs during entry in the tile-to-tile gap due to uneven tile heights in the Shuttle orbiter TPS has been performed. In order to conduct the analysis a technique was developed for predicting the local pressure disturbance caused by a stepped tile. In addition, a method was developed for calculating the air flow rates in the tile-to-tile gaps, and for predicting the temperature level of the gas ingested from the boundary layer. A thermal analysis was conducted on the stepped tile configuration to determine the extent of heating on the tile sidewalls, the filler bar, and the SIP due to the hot air flow in the gap. Combinations of tile step heights and tile-to-tile gaps that could cause varying degrees of damage to the filler bar on the lower fuselage and wing were determined. The magnitudes of the predicted step heights and gaps were comparable to the step heights and gaps that were observed in damaged regions after each of the initial flights of the Shuttle. The results indicate that the steps and gaps must be controlled within tight tolerances during tile installation and the tolerances must be maintained in flight. If the tolerances cannot be maintained, tile-to-tile gap filler would be an alternative. Analysis indicated that a half-height, flexible, ceramic fiber blanket gap filler prevents charring of the filler bar. At the present time, the TPS is inspected after each flight for damaged filler bar. If there is sufficient damage, the filler bar is replaced and a rigid temporary gap filler is added.

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TABLE 1.- STS-1 POST-FLIGHT MEASUREMENT EXTREMES IN DAMAGED FILLER BAR AREAS

TILE/TILE STEPS	-0.099 TO +0.12 in.
TILE/TILE GAPS	0.010 TO 0.13 in.

CATEGORIZATION OF DAMAGED FILLER BAR

CATEGORY	TEMPERATURE	DAMAGE
1	970 °F	RTV DISCOLORED
2	1100 °F	RTV CHARRED
3	1375 °F	RTV AND FILLER BAR CHARRED

TABLE 2.- PEAK FILLER BAR TEMPERATURES AT FUSELAGE LOCATION

STEP, INCH	INITIAL GAP, INCH	MAX GAP, INCH	PEAK FILLER BAR TEMPERATURE, °F	CATEGORY
0.04	0.05	0.067	970	1
0.10	0.05	0.092	1500	3

INSTALLATION SPECIFICATION: TILE STEP - 0.030 INCH MAX
TILE GAP - 0.065 INCH MAX

TABLE 3.- PEAK FILLER BAR TEMPERATURES AT WING LOCATION

STEP, INCH	INITIAL GAP, INCH	MAX GAP, INCH	PEAK FILLER BAR TEMPERATURE, °F	CATEGORY
0.017 (INSTALL SPEC)	0.05	.063	864	
0.03	0.05	.080	1286	2
0.06	0.05	.103	1747	3

TABLE 4.- PERMEABILITY TEST RESULTS FOR FIBERFRAX 880JH (CARBORUNDUM CO.) CERAMIC FIBER BLANKET

Flow, Std. cu. ft.	P_1, psf	P_2, psf	$\dot{m}$, lbm/sec.	$-\frac{dP}{dx}$, psf/ft.	K_p, ft.^{2}
3.53×10^{-3}	200.5	83.5	4.409E-6	1114	3.66E-10
7.06×10^{-3}	273.4	83.5	8.818E-6	1816	3.57E-10
10.60×10^{-3}	338.3	83.5	1.323E-5	2426	3.40E-10
14.13×10^{-3}	396.8	83.5	1.764E-5	2893	3.24E-10
17.66×10^{-3}	448.3	83.5	2.205E-5	3474	3.14E-10
14.13×10^{-3}	398.5	83.5	1.764E-5	2999	3.21E-10
10.60×10^{-3}	342.5	83.5	1.323E-5	2466	3.31E-10
7.06×10^{-3}	278.5	83.5	8.819E-6	1856	3.45E-10
3.53×10^{-3}	203.3	83.5	4.409E-6	1141	3.54E-10

Sample thickness = 0.093 in.
Sample width = 1.26 in.
Sample length = 1.26 in.
Sample frontal area = 0.1172 in.^{2}
Standard temperature = 70 F
Standard pressure = 2115 psf

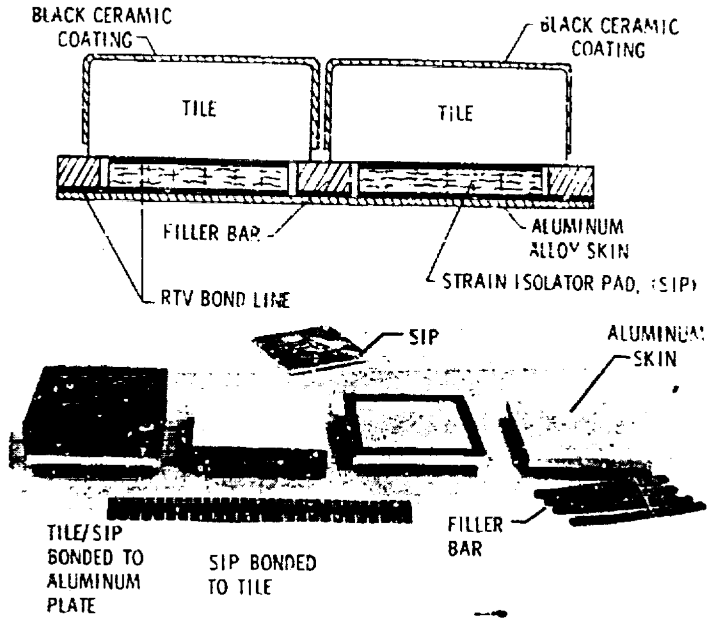

Figure 1.- Tile configuration on lower surface of orbiter.

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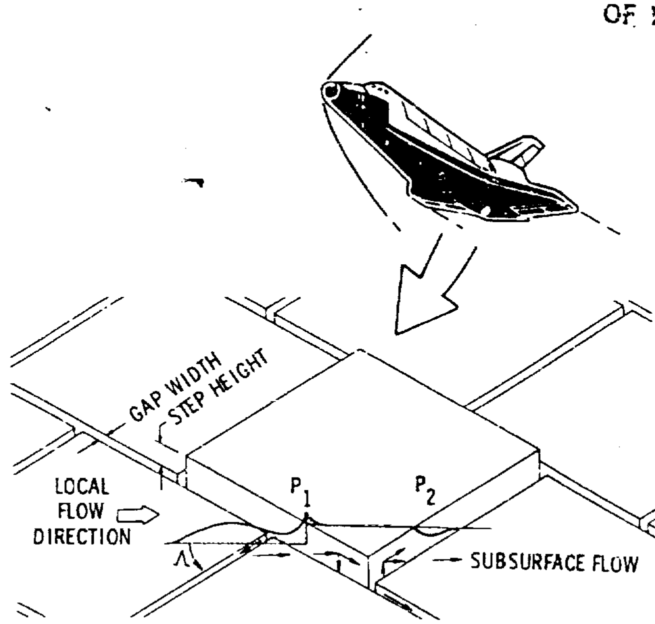

Figure 2.- Local pressure disturbances caused by a stepped tile.

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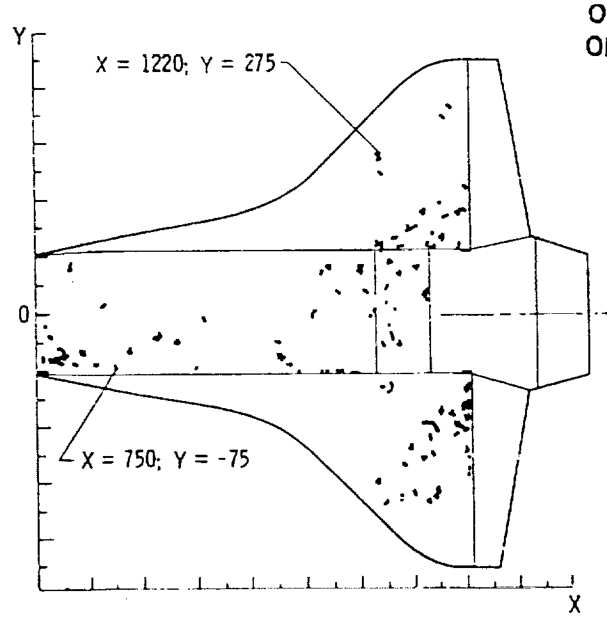

Figure 3.- STS-1 orbiter lower surface - charred filler bar locations for analysis.

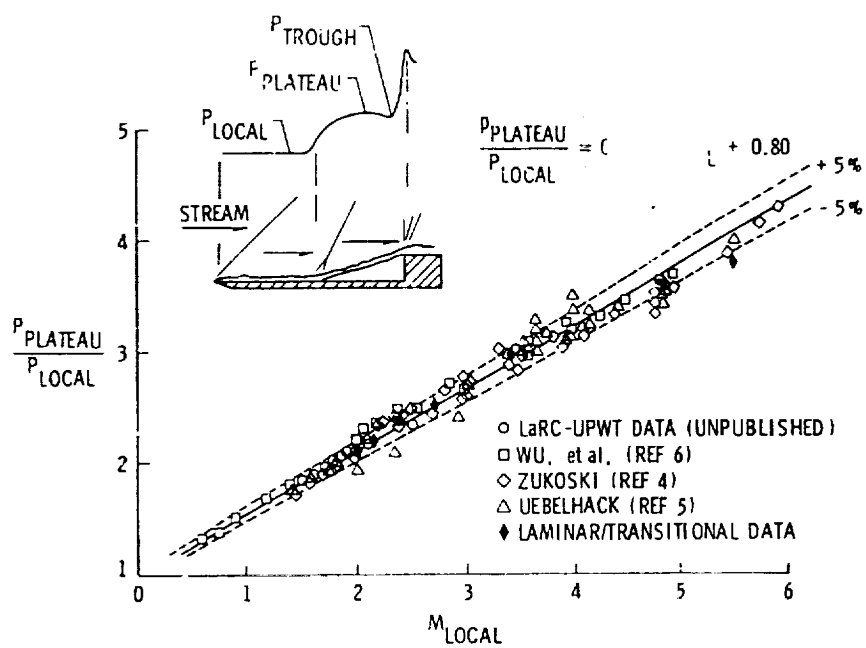

Figure 4.- Plateau pressure correlation.

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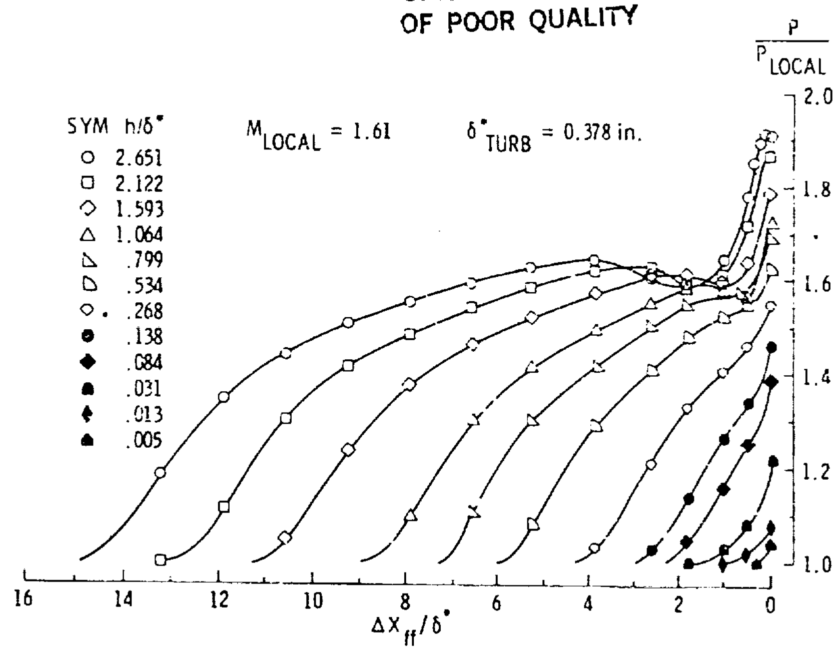

Figure 5.- Experimental pressure data for forward-facing steps.

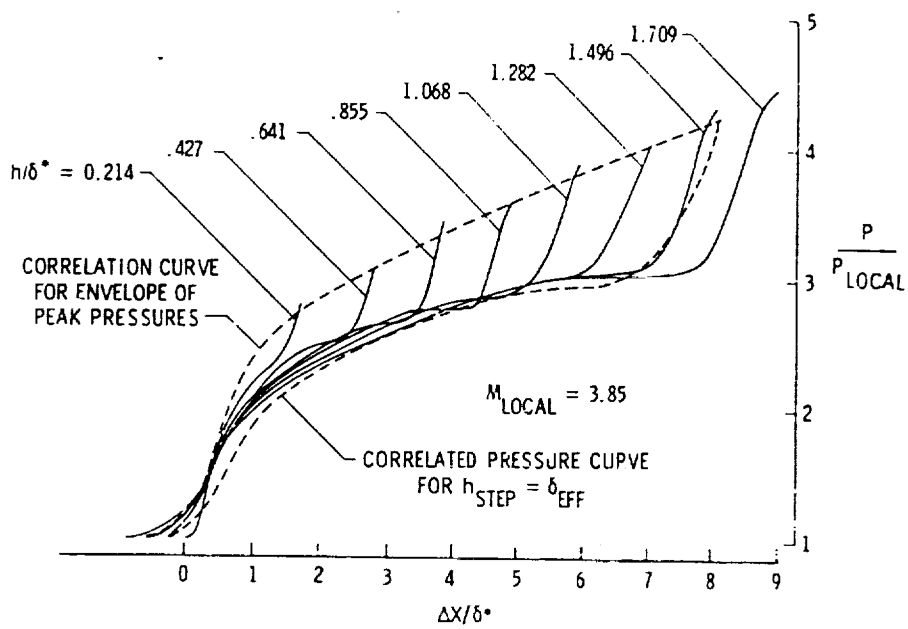

Figure 6.- Comparison of correlation and experimental pressure profile data.

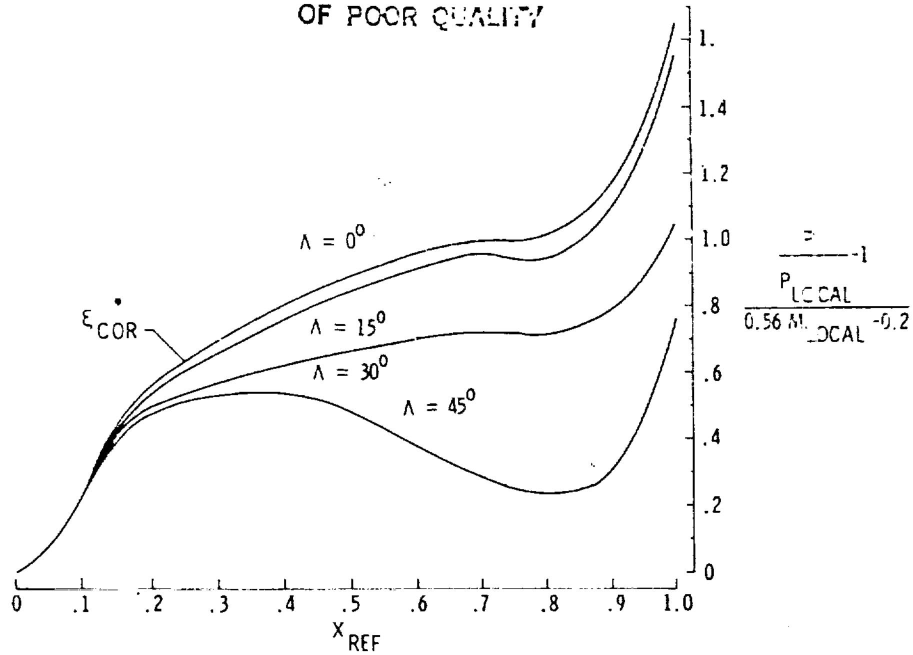

Figure 7.- Pressure distributions ahead of unswept and swept forward facing steps.

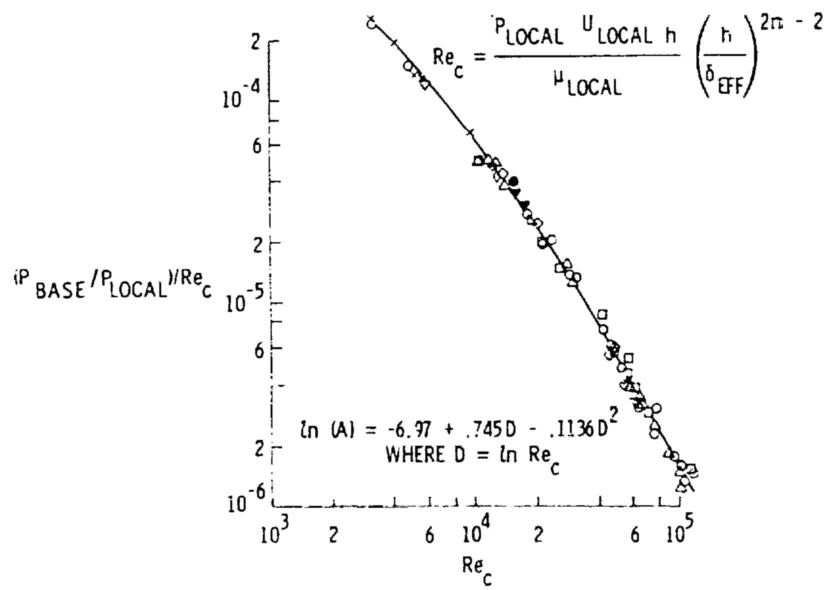

Figure 3.- Base pressure correlation (reference 9).

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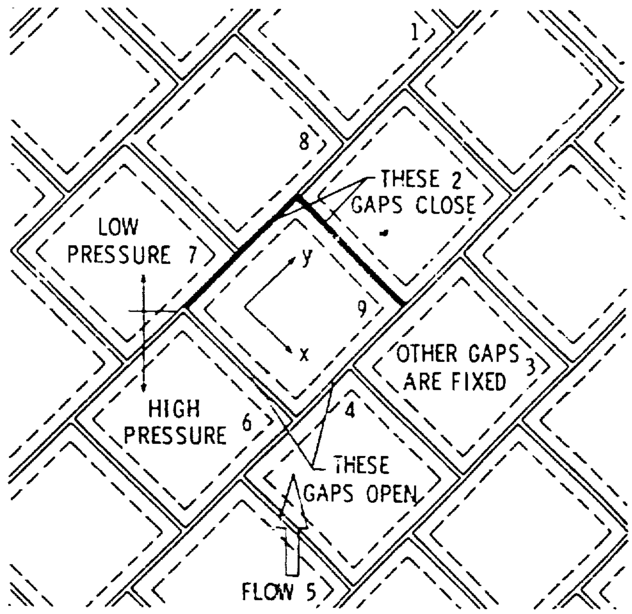
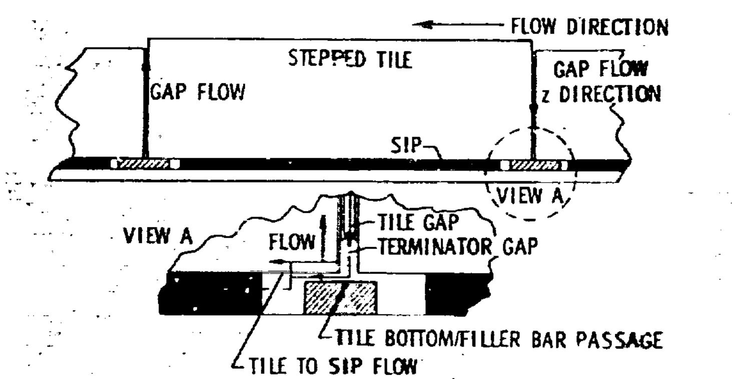


Figure 9.- Flow model tile array.



$$\dot{M}_{GAP} = -\frac{1}{12}\ \frac{\rho W^2 A_c}{\mu}\ \frac{DP}{DS} \qquad \dot{M}_{SIP/TILE} = \frac{K_p \rho A_c}{\mu}\ \frac{DP}{DS}$$

Figure 10.- Typical flow paths in Shuttle tile flow model.

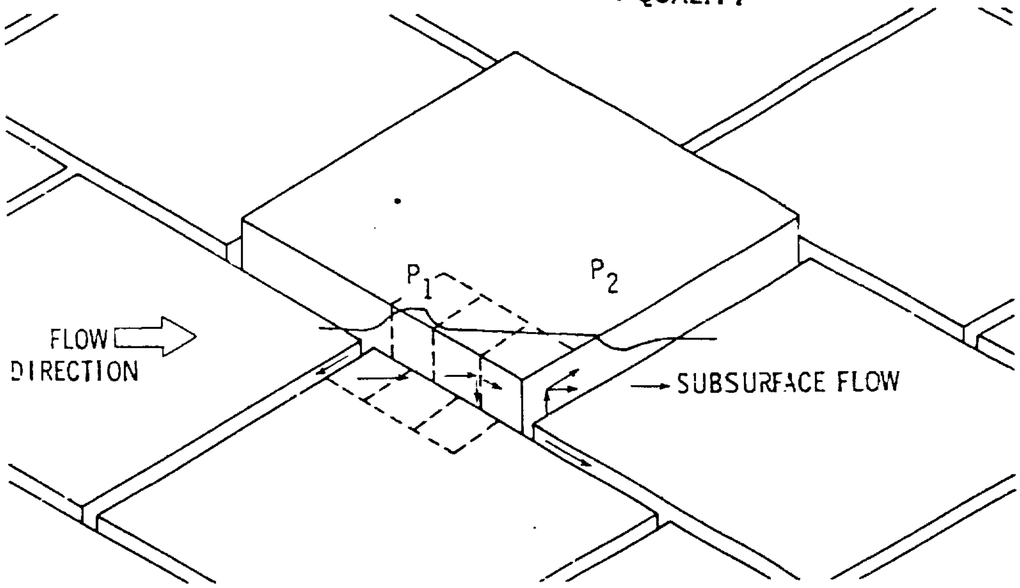


Figure 11.- Region modeled for thermal analysis.

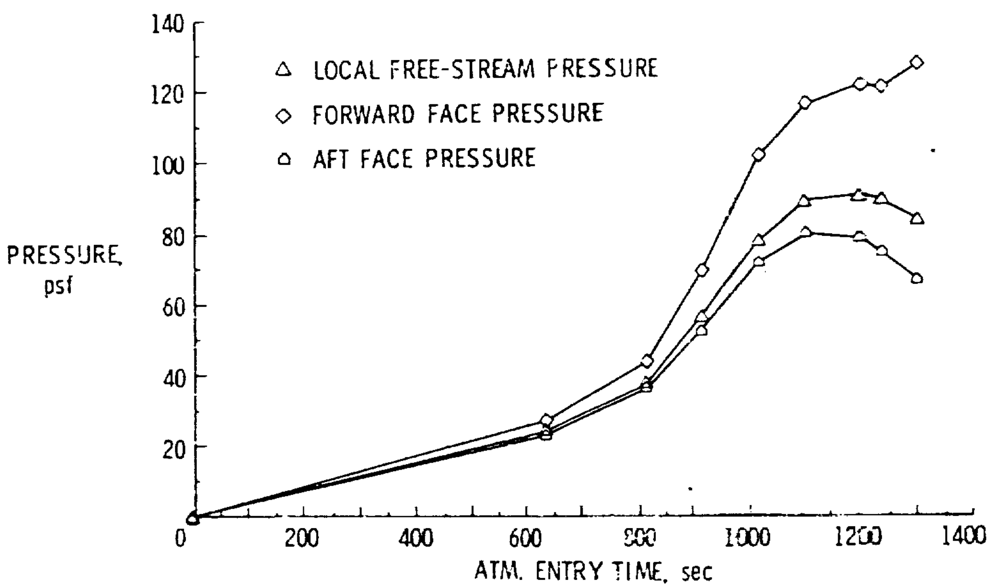


Figure 12.- Pressures at fuselage location, 0.1-inch step.

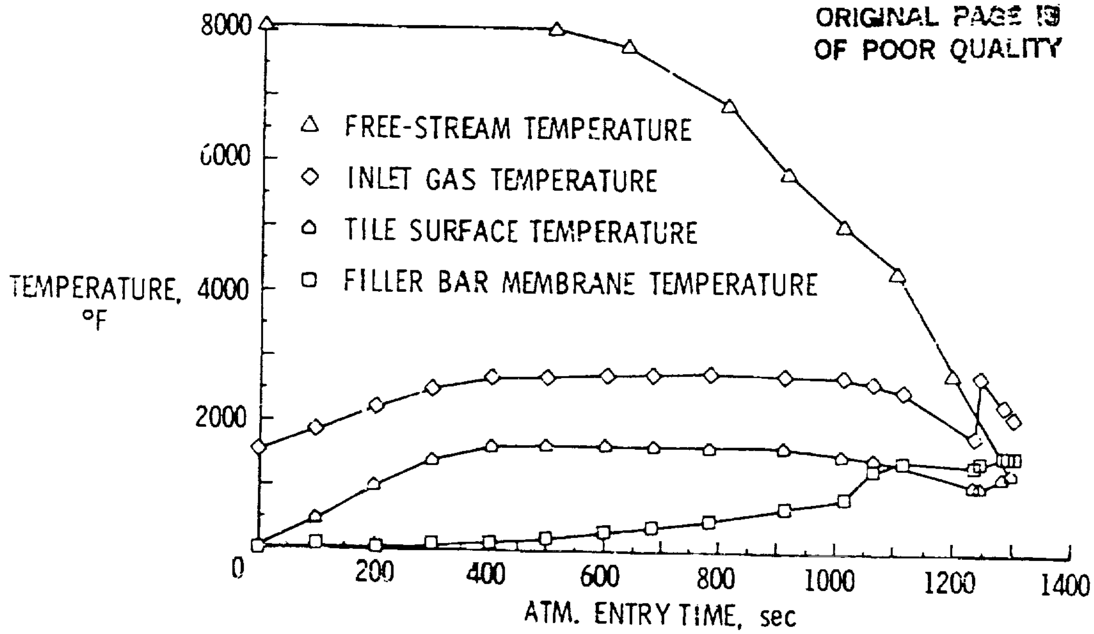


Figure 13.- Gap temperatures at fuselage location, 0.1-inch step.

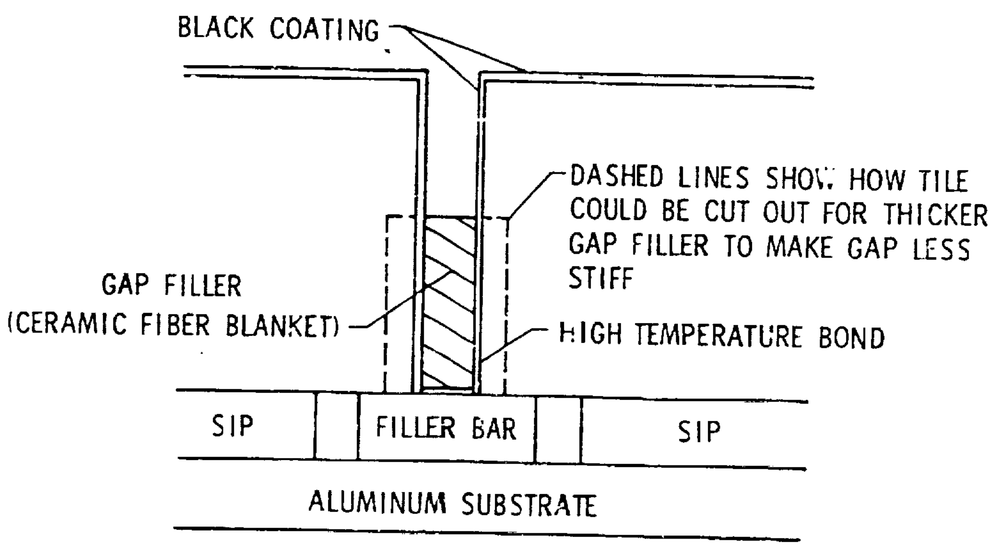


Figure 14.- Ceramic fiber gap filler concept.

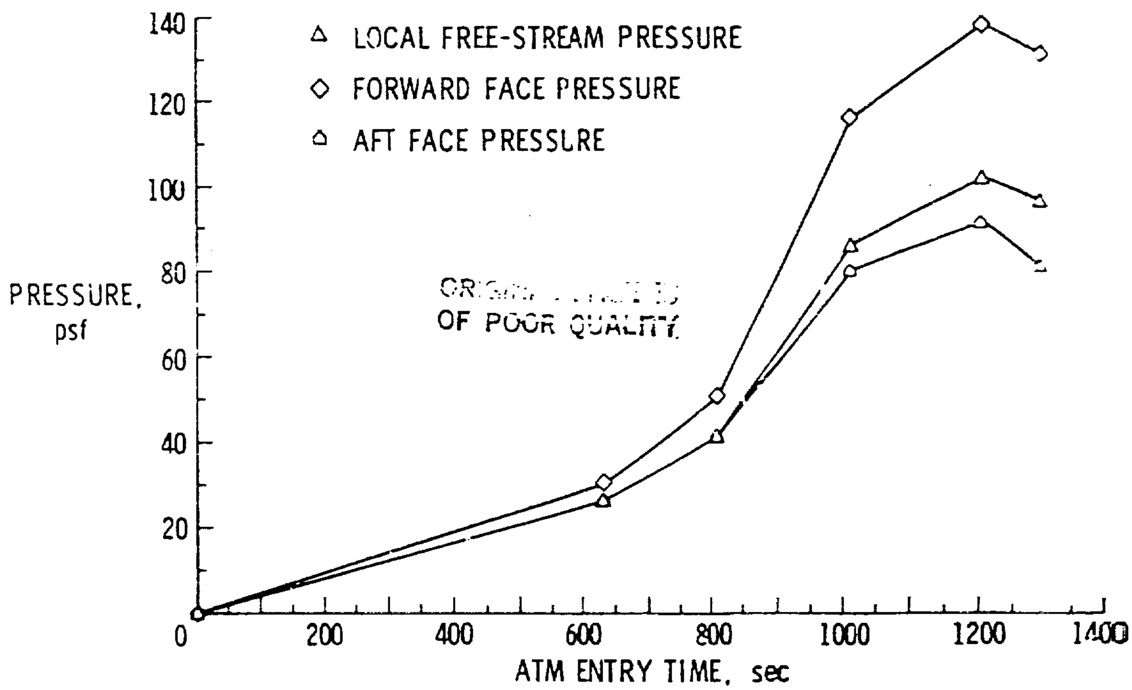


Figure 15.- Pressures at wing location, 0.06-inch step.

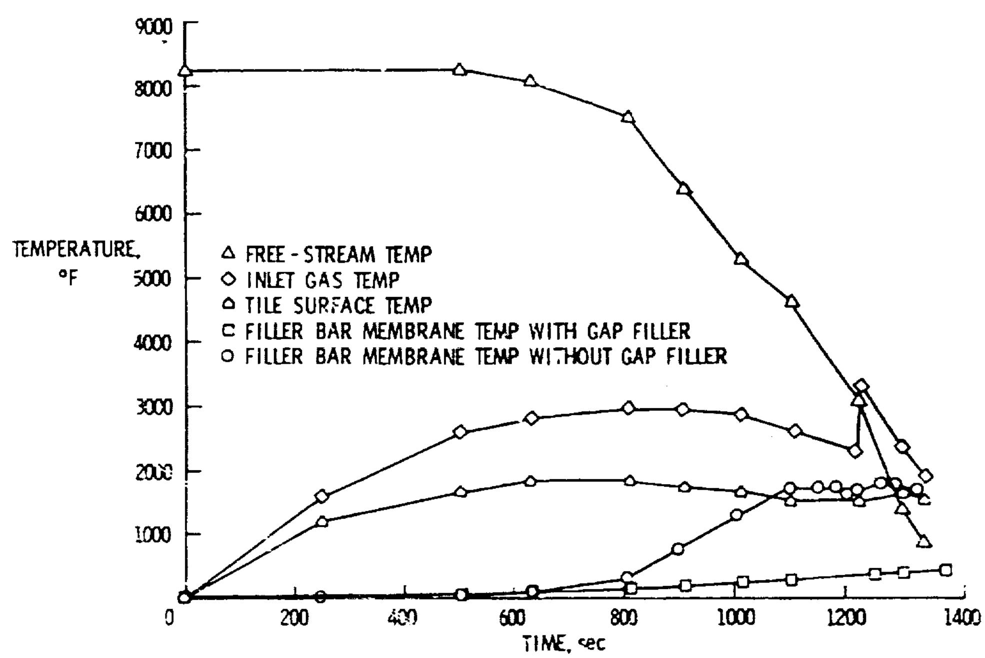


Figure 16.- Gap temperatures at wing location, 0.06-inch step.