SIMULATED REENTRY HEATING BY TORCHING

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ABSTRACT

The two first order reentry heating parameters are peak heating flux (W/cm^2) and peak heat load (kJ/cm^2). Peak heating flux (and deceleration, gs) is higher for a ballistic reentry and peak heat load is higher for a lifting reentry. Manned vehicle reentries are generally lifting reentries at nominal 1-5 gs so that personnel will not be crushed by high deceleration force. A few off-nominal manned reentries have experienced 8 or more gs with corresponding high heating flux (but below nominal heat load).

The Shuttle Orbiter reentries provide about an order of magnitude difference in peak heating flux at mid-bottom (TPS tiles, ~ 6 W/cm^2 or 5 BTU/ft^2- sec) and leading edge (RCC, ~ 60 W/cm^2 or 50 BTU/ft^2- sec). Orion lunar return and Mars sample lander are of the same order of magnitude as orbiter leading edge peak heat loads. Flight temperature measurements are available for some orbiter TPS tile and RCC locations.

Return-to-Flight on-orbit tile-repair-candidate-material-heating performance was evaluated by matching propane torch heating of candidate-materials temperatures at several depths to orbiter TPS tile flight-temperatures. Char and ash characteristics, heat expansion, and temperature histories at several depths of the cure-in-place ablator were some of the TPS repair material performance characteristics measured. The final char surface was above the initial surface for the primary candidate (silicone based) material, in contrast to a receded surface for the Apollo-type ablative heat shield material.

Candidate TPS materials for Orion CEV (LEO and lunar return), and for Mars sample lander are now being evaluated. Torching of a candidate ablator material, PICA, was performed to match the ablation experienced by the STARDUST PICA heat shield. Torching showed that the carbon fiberform skeleton in a sample of PICA was inhomogeneous in that sample, and allowed measurements (of the clumps and voids) of the inhomogeneity.

Additional reentry heating-performance characterizations of high temperature insulation materials were performed.

INTRODUCTION

The NASA space exploration, “Constellation”, program has the Orion spacecraft as the Earth atmosphere reentry vehicle for return from the International Space Station and the Moon after retirement of the Space Shuttle system. The Orion spacecraft, a larger version of the Apollo reentry capsule, and Mars sample lander (MSL) capsules are designed to have ablative thermal protective systems (TPSs). The prospective ablative materials need to be characterized and validated by simulated reentry heating tests.

The two first order reentry heating parameters are peak heating flux (W/cm^2) and peak heat load (J/cm^2). In general,, peak heating flux (and deceleration, gs) is higher for a ballistic reentry, and peak heat load is higher for a lifting reentry. Manned vehicle reentries are generally lifting reentries at nominal 1-5 gs so that personnel will not be crushed by deceleration. Some off-nominal manned reentries have experienced 8 or more gs (refs. 1 and 2) with corresponding high peak heating flux. In general, the peak heating load (not the peak heating flux) is the most severe or limiting parameter for TPS systems. To first order approximation, the peak heat load is correlated with reentry kinetic energy per unit area. The reentry mass per unit area for the Space Shuttle Orbiter is about 210 Kg/m^2 (ref. 3 & 4) and the reentry velocity is about 7.9 km/sec. The heating flux at mid-bottom of the Space Shuttle orbiter is about 6 W/cm^2 or 5 BTU/ft^2-sec (ref.5) and the heating flux of the wing leading edge (reinforced carbon carbon, RCC) is about 60 W/cm^2 or 50 BTU/ft^2-sec (ref. 6). The peak heating period is about 1000 seconds (ref. 5). The reentry mass per unit area for the STARDUST capsule is about 90 Kg/m^2 (ref. 7) and the reentry velocity was about 13 km/sec. The reentry mass per unit area for the Orion spacecraft is about 425 Kg/m^2 (ref. 8) and the reentry velocity is about 11km/sec. The reentry mass per unit area of the Apollo Command Module was about 380 Kg/m^2 (ref. 9). The peak heat load for the orbiter TPS tiles (which experience most of the reentry heating is about 6 KJ/cm^2 (ref. 5), for the STARDUST capsule, about 28 KJ/cm^2 (ref. 7), and for the Orion spacecraft about 70 KJ/cm^2 (ref. 7). The peak heating load of the nose and wing leading edge of the Space Shuttle is about ten times higher (ref. 6) than the heating load of the TPS tiles. Most of the kinetic energy of these spacecraft goes into heating the ambient air. About 1% of the kinetic energy of these spacecraft is converted to spacecraft heating. The relatively low reentry heating per unit area for the Space Shuttle Orbiter tiles is due to the Orbiter’s very large acreage (~500 m^2, ref. 4), reentry heating surface.

The heat protection performance of the Space Shuttle TPS tiles and wing leading edge RCC is exceptional. However, as demonstrated by the Columbia accident (ref. 10) it is both fragile and maintenance intensive. Following the Columbia accident "Return-to-Flight" on-orbit TPS tile repair-candidate-material reentry-heating performance was evaluated by matching propane torch heating of candidate-materials temperature histories at several depths to Orbiter tile flight-temperature histories. Orbiter TPS tiles were torched to establish torch parameters to duplicate the flight temperature histories (ref. 5). Char and ash strength as a function of depth, adhesion, integrity, heat expansion, and temperature gradients with depth were some of the TPS repair material performance characteristics measured for a variety of the silicone based materials. The final char surface was above the initial surface for the primary candidate material in contrast to a receded surface for the Apollo-type ablative heat shield materials.

Candidate TPS materials for the Orion CEV (LEO and lunar return), and for Mars sample return are now being evaluated. Torching of a candidate material, PICA, was performed to match ablation depth experienced by the STARDUST PICA heat shield. Torching showed that the carbon fiberform skeleton in a sample of PICA was inhomogeneous at the millimeter scale, and allowed measurements (of the clumps and voids) of the inhomogeneity.

Additional reentry heating-performance characterizations of candidate materials can be performed by matching torching parameters and setup to give peak heating flux and peak heat load as determined by flight experiments and computational fluid dynamics computations.

PROPANE HEATING TESTS

The maximum adiabatic flame temperature for propane in air is 1995C(3623F) (ref. 11). The heat of combustion of propane is 50 x 10^6 J/kg (21,500 BTU/lb)(ref. 12). The propane use of the torch used in these tests was 34 gm/hr = 600 watts (0.090 lb/hr = 0.6 BTU/sec). The hottest portion of the flame has a diameter of about 1/2 cm so the peak heat output of the torch is about 2400 W/cm^2. The heat to a surface can be computed by comparing temperatures of torch heated orbiter TPS materials to corresponding flight temperatures for which the reentry heating is known. Ablation depths of torched samples can also be compared to the ablation depths of the STARDUST capsule. Heating intervals with a propane torch can be selected to match heating loads of reentering spacecraft.

CEV PICA Tests

A 1.3 cm x 1.5 cm x 2.5 cm sample of PICA was obtained from JPL as part of a CEV TPS characterization program. Three small junction (gage 30), K thermocouples were embedded in this sample, one at 0.2 cm from the surface, one at 0.65 cm from the surface, and one 1.9 cm from the surface. The 2-foot thermocouple leads were connected to a four channel data logger. The PICA sample was inserted into a Shuttle TPS tile-core collar for positioning with the torch. The PICA sample and collar were positioned in a propane flame for 10 minutes and for 30 minutes. The temperature histories of the 30 minute torching are presented as figure 1. The 0.2 cm deep thermocouple reached 975C in 8 minutes during the first torching. The PICA ablated below the initial surface 0.2 cm depth during the second torching and the exposed thermocouple reached 1230C. The ablation depth from the second torching is about the same as experienced by the STARDUST capsule stagnation area (ref. 7).

A second sample of JPL PICA was torched. Figure 2 is a photograph of the PICA before torching. Figure 3 is a photograph after torching. Four K thermocouples were embedded in this sample, at 0.2 cm, 0.65 cm, 1.0 cm, and 1.9 cm depth. The PICA was placed in Shuttle TPS tile-core collar, and positioned in the propane flame similar to the first sample. The temperature histories are presented in figure 4. This sample of PICA ablated more than 0.2 cm at 20 minutes of heating, exposing the shallowest thermocouple and saturating it. A tongue of denser fiberform (figure 3) was less ablated than surrounding areas and the resulting uneven surface probably caused the similar temperature histories for the 0.65 cm and 1.0 cm depth thermocouples.

Large scale (centimeters) color variation streaks were observed in billets of PICA which were to be machined into pucks for arcjet testing for the MRL program. Small scale (millimeter) color streaks (figure 5) were also observed in the JPL supplied PICA sample. A portion of the JPL supplied PICA was torched for 30 minutes and then compared with virgin PICA with several microscopes. Figure 5 shows color streaks (~1 mm x 10 mm) and a 1 mm carbon particle in virgin PICA. Figure 6 (pre-torching) shows a 1 mm x 3 mm void in the carbon fiberform. Figure 7 shows a fused carbon clump in the fiberform. Figure 8 shows voids and needles (partially oxidized carbon fibers) in the torched PICA.

It is concluded that the small scale dark streaks in this virgin PICA sample result from inhomogeneities in the carbon fiberform.

MSL PICA Tests

Thin (~0.40 cm) samples of light and dark MSL PICA were torched to further investigate color variations. Two K-thermocouples were placed on the back side of each thin section (figure 9). A 2.5 cm wide glass slide was used to clamp the thermocouples to the PICA. The PICA samples with glass slides were held in forceps and positioned in a propane torch flame for 5 minutes. A photograph of the torched thin PICA samples is presented in figure 10. The temperature histories are presented in figure 11. One thin PICA sample was inadvertently torched on the glass cover (which broke) for a few seconds. One of the thermocouples came open during the testing and the temperature on the hottest area of the back side is not available. The torched (front side) of the two thin samples are similar in appearance, but there was significant erosion (ablation) of the fiberform on the back of the sample which had the broken glass cover slide. There is a fine, white fiber ash on the torched surface of each of these samples.

Two additional thin light and dark color samples of MSL PICA were prepared for torching because of the problems encountered with the torching of the first two thin samples. The preparation was similar to that of the first two thin samples. One thermocouple was placed at the center of the torch-flame position on the rear surface and the second thermocouple was placed 1 cm away from the center position. 2.5 cm wide glass slides were used to clamp the thermocouples in place. A closeup photograph showing edge effects from the heating is presented as figure 12. A fifth thin PICA ample was clamped to a matching section of TPS tile core to evaluate the effect of the glass slides on the thermocouple measurements. This fifth thin sample was torched twice for five minutes each time. A photograph of this torched sample is presented in figure 13. The temperature histories of the thin PICA samples are presented in figures 14-16.

Four of the five thin samples of torched PICA appear to be layered (or undercut by the torching). That is, the ablation around the edges is not uniform. This apparent layering does not correlate with color, which was relatively uniform for each sample (but varied from sample to sample).

The edge effects seen in the thin samples was not well understood, so torching of larger and thicker samples was performed. A small (~ 2.5 cm across, figure 17) sample, and a larger (~5 cm across, figure 18) sample by 2.2 cm thick of MSL PICA were prepared for torching. Three thermocouples were embedded horizontally at 0.2 cm, 0.65 cm, and 1.0 cm depth in the smaller sample. The thermocouples were potted at side entrance ports with a small amount of 5 minute epoxy. Four K thermocouples were embedded at 0.2 cm, 0.65 cm, 1.0 cm, and 1.9 cm depth in the larger PICA sample. The PICA samples were held in forceps and positioned in a propane torch flame for about 20 minutes (figures 19 and 20). The propane valve was adjusted to have the tip of the inner blue flame 4.4 cm from the torch nozzle. The propane flow was slightly increased periodically during the torching to maintain the inner blue flame at 4.4 cm as the pressure inside the propane bottle decreased slightly due to evaporation of the propane. The small (2.5 cm) sample of PICA was torched for five minutes a second time (figure 21). The small and large 2.2 cm thick samples were subsequently torched for about 10 minutes (figures 22 and 23). The flame diameter was about 0.5 cm and the brightest (hottest) surface char area was about 1.5 cm in diameter. The 0.5 centimeter diameter faint blue flame spreads into a thin (~ 1mm thick sheet of about 5 cm diameter) at the surface of the PICA. The hot center of the propane flame is reduced in oxygen due to nearly complete burning of the propane, but the lower temperature outer regions of the flame are mixed with air. These outer regions are the regions of greatest ablation of the fiberform. The same data logger was used for both the small and large PICA samples; different terminal blocks and thermocouples were used for the two PICA samples.

It is concluded that the large scale color variations in the MSL PICA are due to variations in the fiberform, and that the edge effects or undercutting is due to oxidation.

Orbiter TPS Tile Tests

Many Orbiter TPS tiles have been subjected to many Earth atmosphere reentries and some reentry-flight versus tile depth-temperature-histories are available. A section of flown Orbiter TPS tile was instrumented with K thermocouples. The thermocouples were embedded at 0.2 cm, 0.65 cm, 1.0 cm, and 1.9 cm depths into the tile section (figure 21). The tile was torched several times. There was no apparent change to the tile resulting from the torchings. The temperature histories during one of the torchings of the tile section are presented in figure 22.

Ceramic Insulation Tests

Two types of ceramic insulation are used in TPS testing at LaRC. A low density (0.25 gm/cm^3), and a high density (0.57 gm/cm^3) insulation are used. 7.5 cm x 12.5 cm x 2.5 cm specimens of each density of ceramic insulation were instrumented with K thermocouples (figures 24 and 25) in a manner similar to the Orbiter TPS tile. The temperature histories during torching at depths of 0.2 cm, 0.65 cm, 1.0 cm, and 1.9 cm are presented in figures 25 and 26. There was no apparent change to the ceramic insulation, other than slight discoloration, resulting from the torching.

TEST RESULTS AND CONCLUSIONS

The temperatures at 0.2 cm, 0.65 cm, and 1.9 cm of the first sample of CEV-JPL PICA are presented in figures 1 and 4.
The temperatures at 0.2 cm are about 200C higher than that of the acreage sites for STS 2 (ref. 9) during the initial heating and before the CEV-JPL PICA ablated enough to expose the top thermocouple to the flame. The ablation depth after about 40 minutes of torching is about the same as experienced by the reentered STARDUST capsule stagnation area (ref. 4).

The torching of a second sample of JPL supplied PICA showed millimeter scale non-uniformities in the PICA fiberform skeleton.

The preliminary torching of a small, thin section of MSL PICA showed apparent edge erosion and fine, white fiber ash. The effect of color variation on ablation was being studied in this test. The apparent edge erosion was studied in subsequent tests on larger samples of MSL PICA, and attributed to oxidation.

Similar torch simulated reentry heating tests were performed on a small section of Shuttle Orbiter TPS tile and two different densities of porous ceramic insulation. The thermal protection performance for the first 10 minutes of simulated reentry heating of the four materials is similar.

These propane-torch simulated-reentry heating tests demonstrate that propane torching can provide important thermal protection performance characterization of candidate reentry TPS materials. These simulated reentry heating tests and this paper are not intended to be a complete or general study of TPS materials characterization and heat protection performance evaluation. Rather, the purpose is to show that torch heating has a place in the complex and generally expensive simulated reentry heating testing, and can be used to identify and economically study some aspects of reentry TPS materials.

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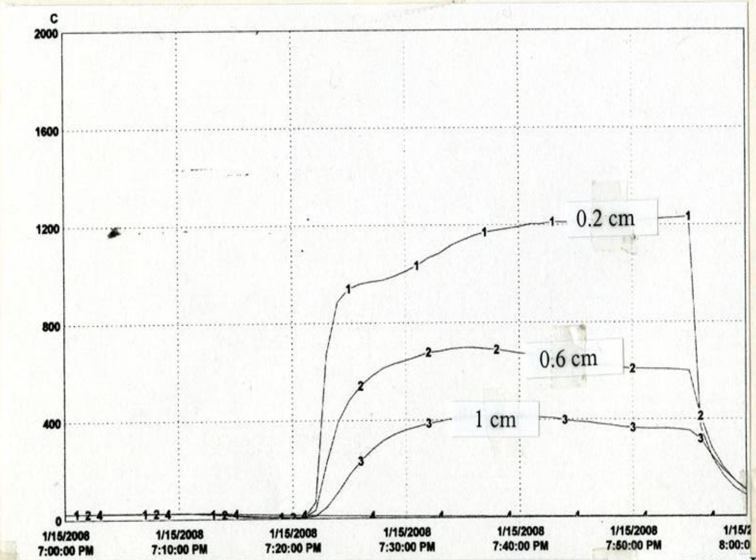

Figure 1. Temperature histories of torch heating of a small sample of JPL PICA.

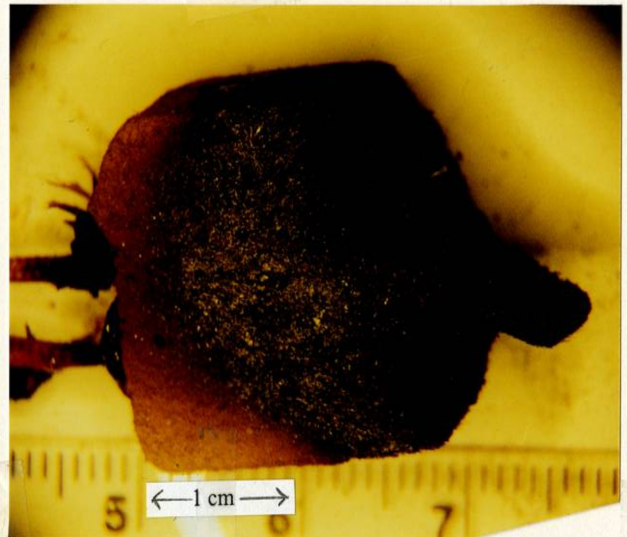

Figure 3. Post-torching photograph of a 2nd sample of PICA.

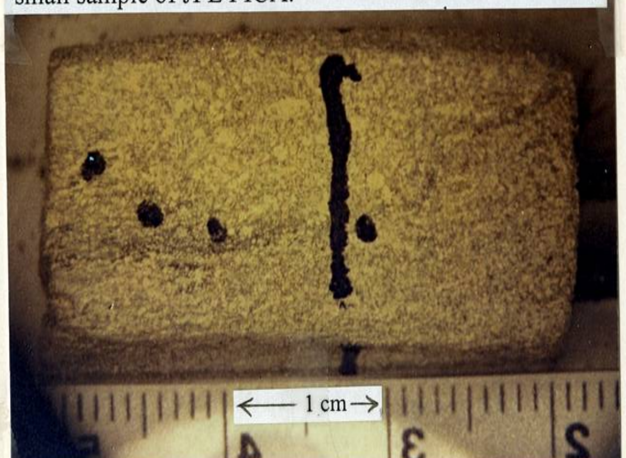

Figure 2. Pre-torching photograph of a 2nd sample of PICA.

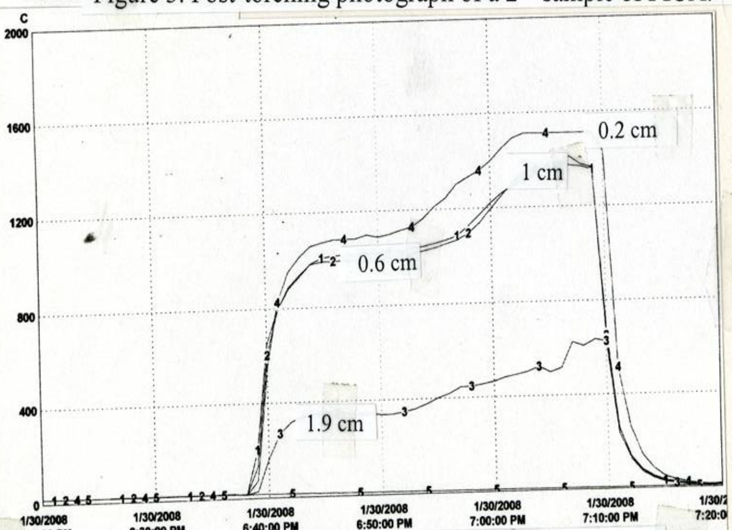

Figure 4. Temperature histories of torch heating of a 2nd sample of JPL PICA.

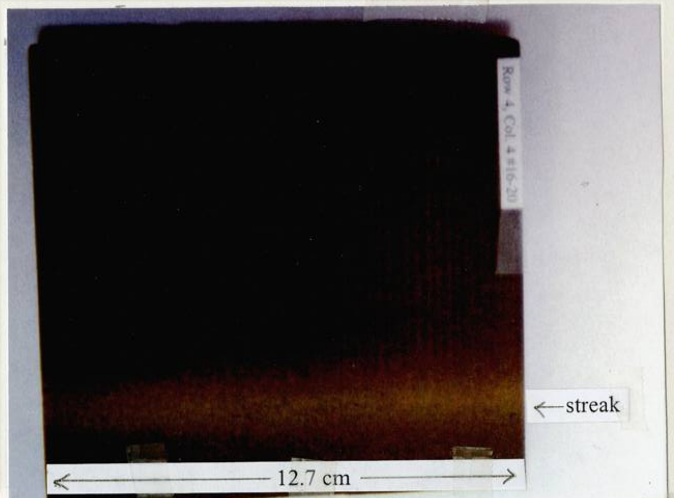

Figure 5. Large scale color streak in MSL PICA.

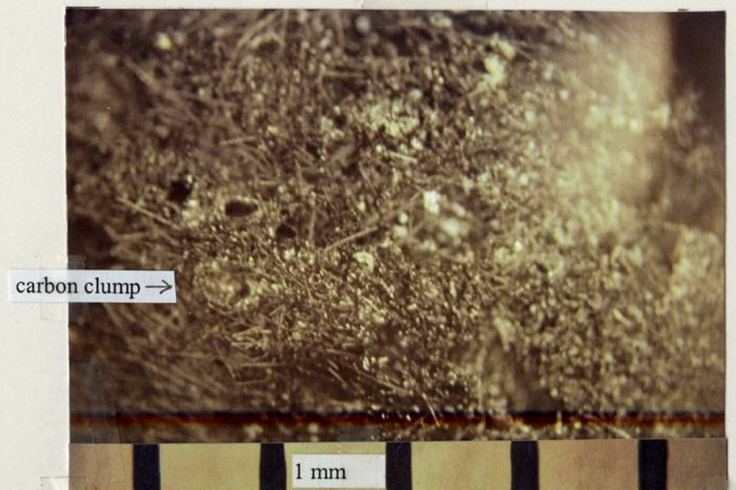

Figure 7. Carbon clump in torched PICA (fiberform).

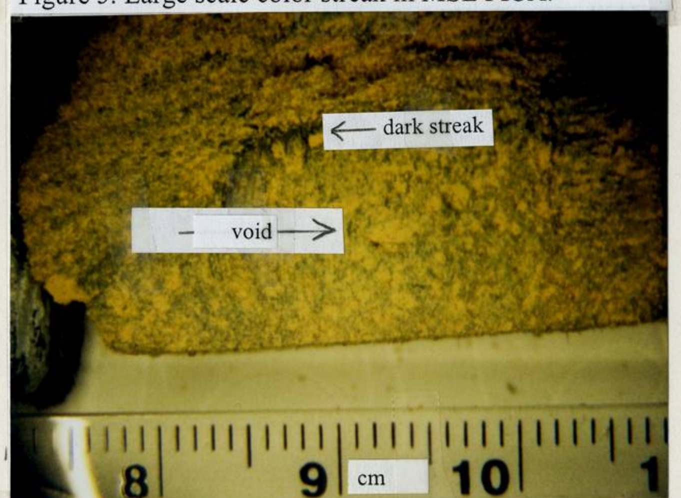

Figure 6. Small scale color streak and fiberform void in JPL PICA.

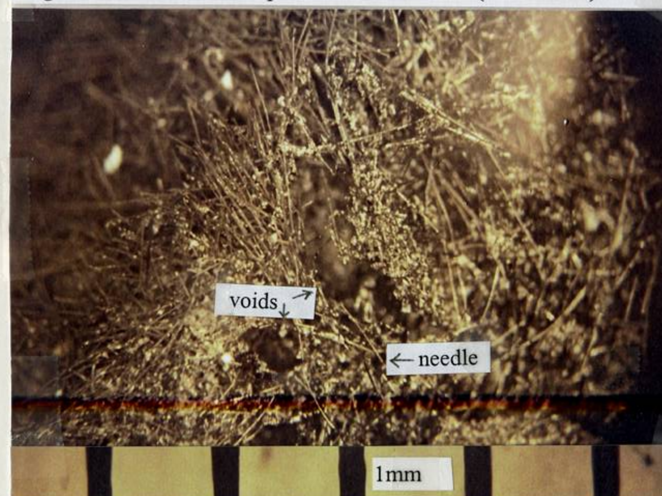

Figure 8. Voids and carbon needles in torched PICA (fiberform).

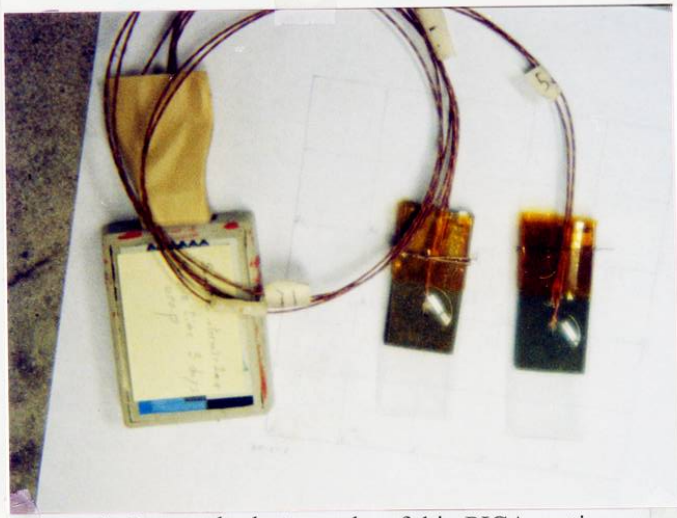

Figure 9. Pre-torch photographs of thin PICA sections.

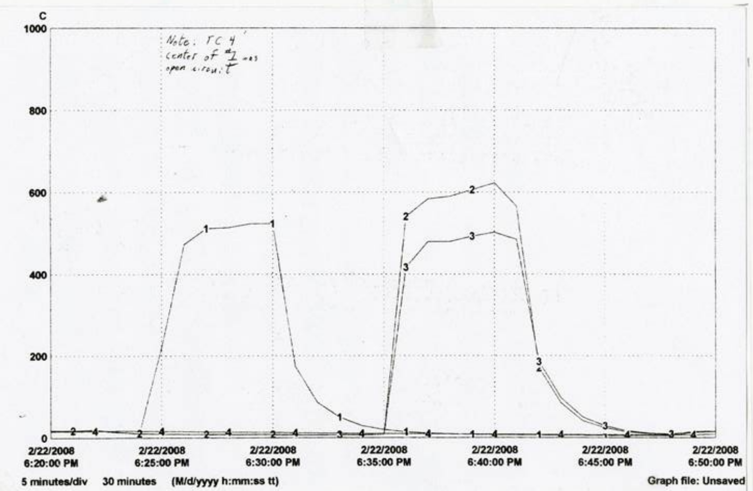

Figure 11. Temperature histories of thin PICA sections.

Figure 10. Post-torchings photograph of thin PICA sections.

Figure 12. Enlarged photograph showing edge effects of torching.

Figure 13. Closeup photograph of torched 5th thin PICA sample.

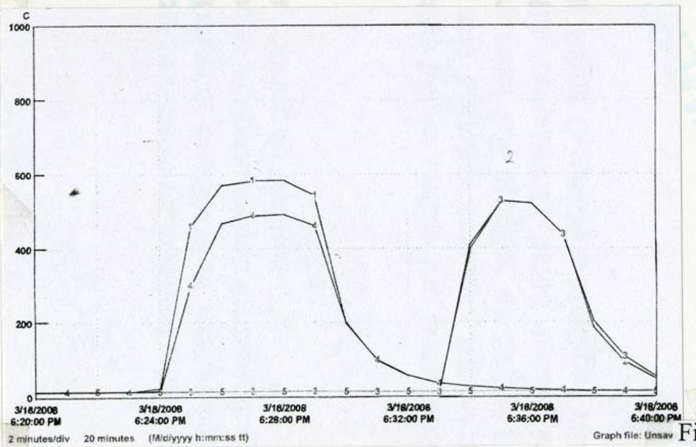

Figure 14. Temperature histories of thin PICA samples 2 and 12.

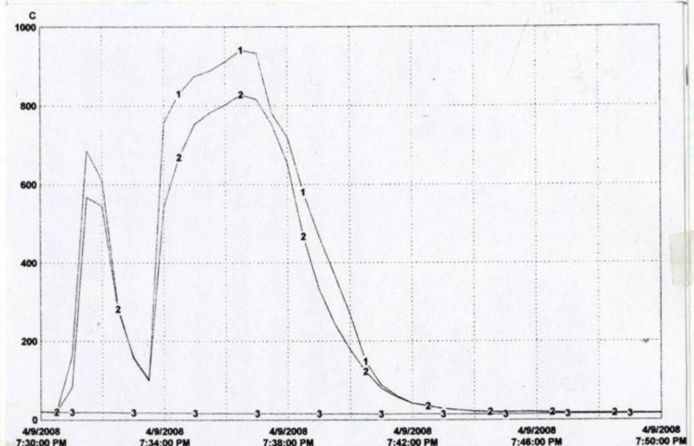

Figure 15. Temperature histories of first torching of 5th thin PICA.

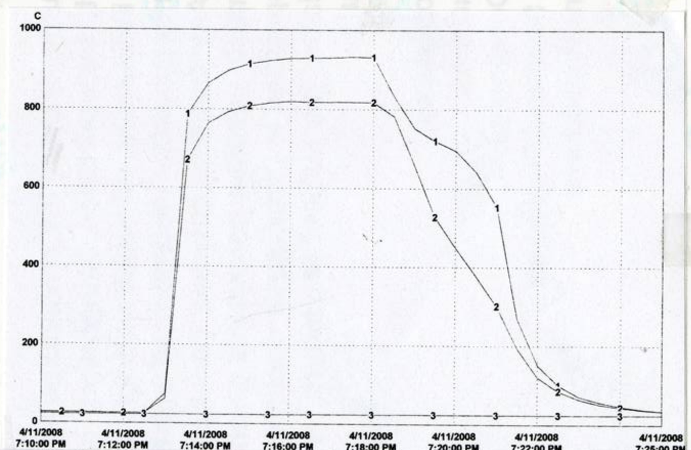

Figure 16. Temperature histories of second torching of 5th thin PICA.

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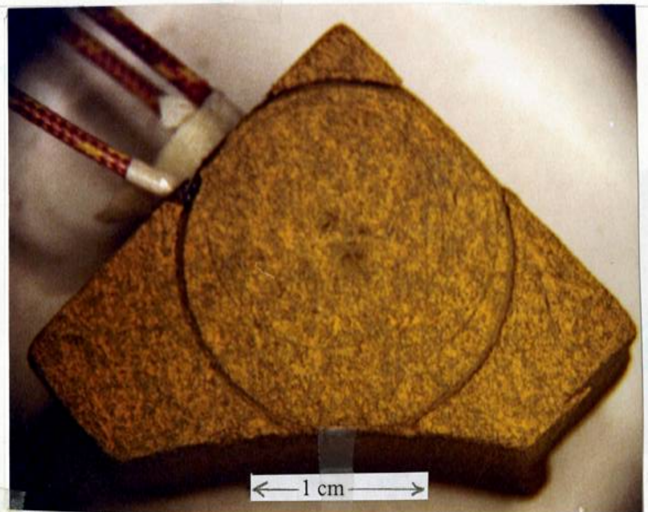

Figure 17. Pre-torch photograph of small 1-inch PICA sample.

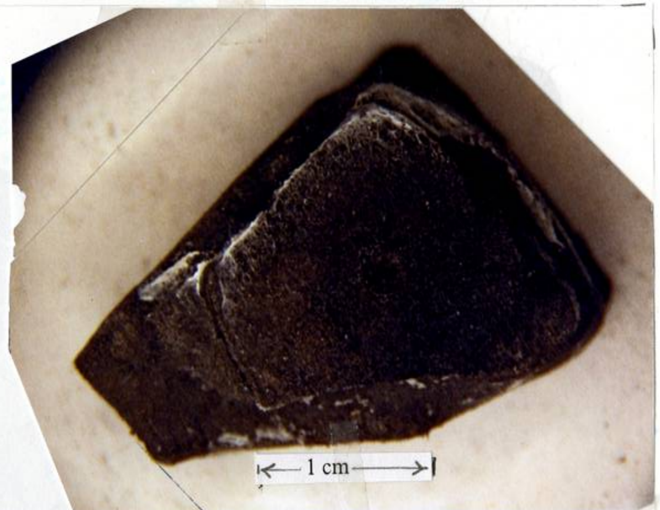

Figure 19. Post-torch photograph of small 1-inch PICA sample.

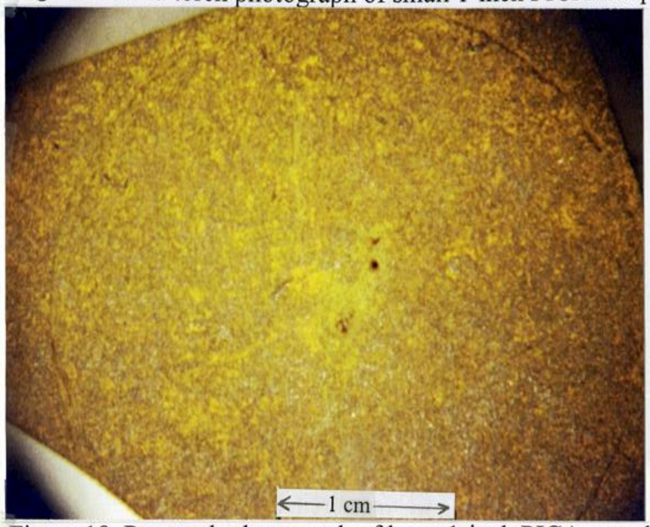

Figure 18. Pre-torch photograph of large 1-inch PICA sample.

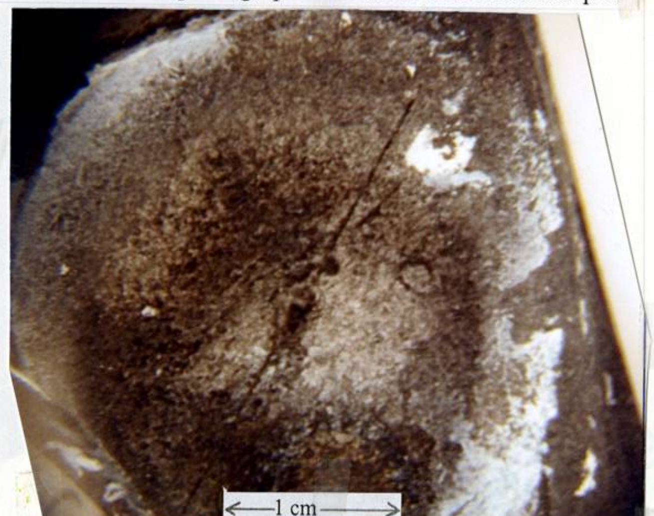

Figure 20. Post-torch photograph of large 1-inch PICA sample.

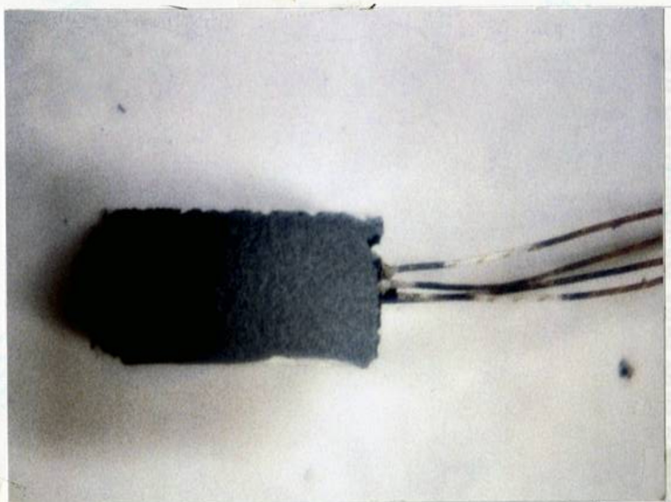

Figure 21. Pre-torching photograph of Orbiter TPS tile section.

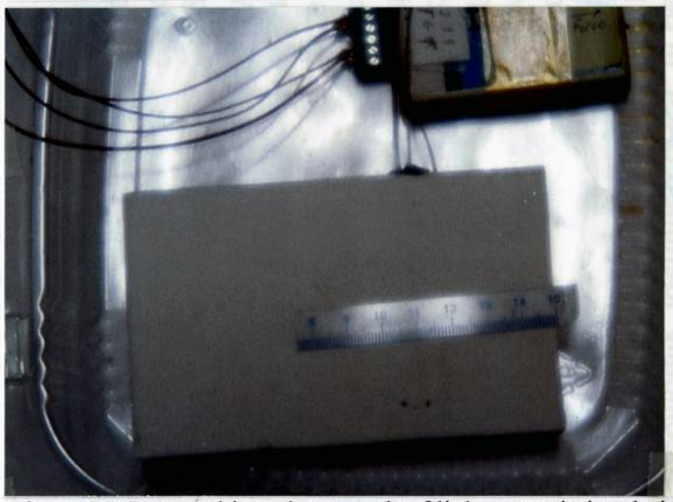

Figure 22. Pre-torching photograph of light ceramic insulation.

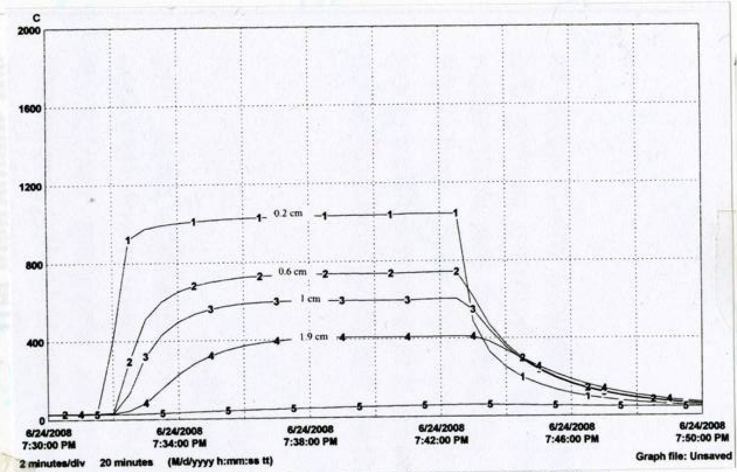

Figure 23. Temperature histories of Orbiter TPS tile.

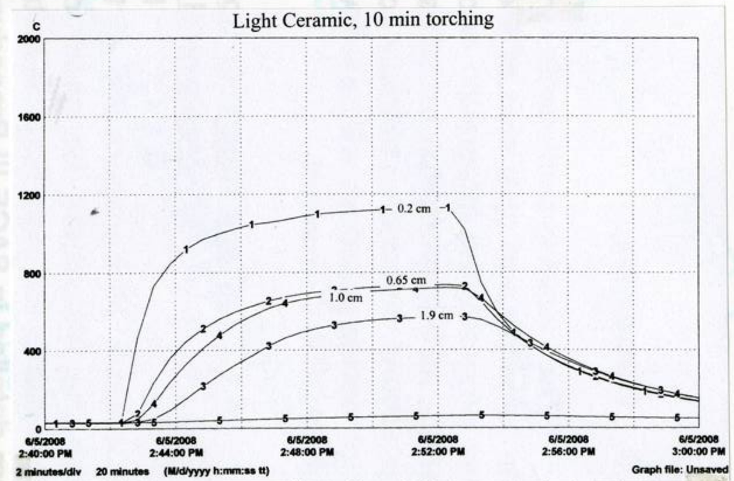

Figure 24. Temperature histories of light ceramic insulation.

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