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Thermal Engineering of Mars Entry Carbon/Carbon Non-Ablative Aeroshell - Part 3

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ABSTRACT

This is Part 3 of a development program to evaluate candidate nonablative aeroshell designs. The primary goal of this C/C aeroshell development task was to demonstrate the feasibility and performance of a lightweight C/C non-ablative aeroshell design that integrates advanced C/C materials and structural configurations. The thermal performance was evaluated by Arc Jet testing at NASA Ames of representative structural models. In this phase of the program, new carbon-carbon materials and structural core designs were evaluated, as well as an alternative aerogel material. The test models were composed of a quasi-isotropic Carbon/Carbon(C/C) front face sheet (F/S), eggcrate or honeycomb core, C/C back F/S, Carbon and resorcinol-formaldehyde aerogel insulation. Part One of this work [1] demonstrated the feasibility through arc-jet testing and Part Two [2] included analytical modeling of the test geometry to validate the design. In this work alternative carbon-carbon material, core construction and oxidation resistant coatings were used as the design variables. Testing was conducted on six test models with the arc jet temperature at nominally 1500 °C. Three design configurations successfully maintained the rear surface below 150°C during 45 seconds of exposure.

INTRODUCTION

A C/C non-ablative aeroshell has many advantages over a standard ablative aeroshell. A C/C aeroshell is non-ablative by nature, and thus would be shape stable during entry. Further, a C/C aeroshell would weigh less than an ablative counterpart, primarily since the ablative layer is eliminated. By utilizing the technology that has been demonstrated under sponsorship from the Mars Exploration Technology Survivability Task, a C/C aeroshell would yield a weight savings over 25% as compared to that of an ablative aeroshell. This lighter weight, shape stable C/C aeroshell structure (having lower possible ballistic coefficients due to the weight savings) would contribute to a more accurate and a more flexible entry profile and make possible a more predictable pinpoint landing.

This technology is well suited for Mars entry and is particularly well suited for landers housing a sample return vehicle, where weight savings are at a premium. This technology also would be usable for high deceleration aerobraking in Mars, Earth, Venus or outer planet atmospheres, where it could be applied for aerocapture or atmospheric entry.

The primary goal of this C/C aeroshell development task was to demonstrate the feasibility and performance of a lightweight C/C non-ablative aeroshell design that integrates advanced C/C materials and structural configurations, low density carbon aerogel for thermal insulation, and thermally stable oxidation resistant coatings. Also, this task has developed thermal modeling design tools for use in designing scaled up aeroshell for flight systems. Figure 1 shows the cross section for the test model used in the arc jet testing. The aeroshell design composed of Carbon/Carbon (C/C) face sheets and C/C core structure with a carbon aerogel insulation layer. The front exterior surface was coated with SiC for oxidation resistance and the front surface of the middle plate was coated with copper to provide a radiation shield.

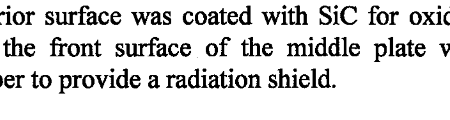


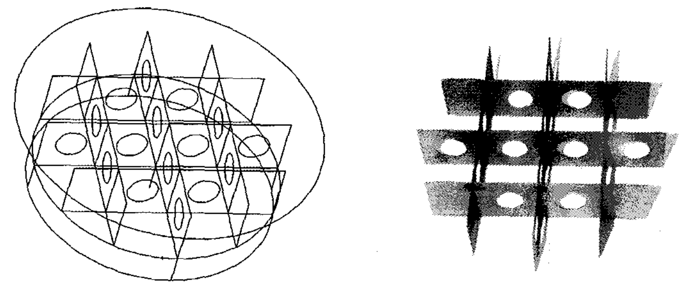
Figure 1: Configuration of Arc Jet Test Models

The carbon aerogel provides significant thermal isolation due to its low thermal conductivity and its minimal radiative transmittance. The thermal properties of carbon aerogel have been investigated by a series of investigators (e.g. ref [3]-[4]). The temperature dependent property of carbon aerogel used in this study as well as details of the thermal modeling of this testing was presented in Reference [2].

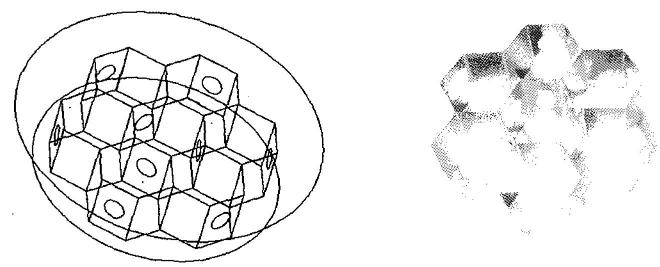
MATERIALS TEST MATRIX

A test matrix of 12 carbon-carbon test models was developed to characterize the performance of manufacturing and materials performance. A major goal of this phase of the program was to develop manufacturing processes that could be scaled to larger aeroshell concepts. Of the twelve test models that were fabricated, six were eventually tested at the Arc jet facility at NASA Ames. The entire test model material configuration that were fabricated is listed in Table 1. In this test matrix, the P-30X in tape form was chosen because it is well known that during processing to form a high conductivity carbon-carbon composite [5]. When the P-30X is processed in tape form it provides a high strength and modulus structural material at thin cross sections. Recent work has shown that the XN-50 fiber has a similar fiber morphology that also allows graphitization to a high crystallinity that converts to a high conductivity material. The XN-50 fiber was available in a fabric form, which provided a corollary to the tape lay-up of the P30X. Two core concepts were evaluated in this series of testing. The first was the eggcrate core structure used in phase 2 of this program and the second was a honeycomb structure. These are shown in Figures 2a and 2b. T-300 was chosen for the fiber for the core since it is known that it can be developed with a lower relative thermal conductivity carbon-carbon composite material even at high processing temperatures. Lay-ups were always such as to maintain balance in quasi-isotropic flat plates. Carbon aerogel was used in all test models, with the exception of A1 in which a novel Resorcinol-Formaldehyde/Silica Dioxide was evaluated.

The processing sequence for the faceplates and the material used in the egg-crate core was composite cure, carbonization, followed by CVD infiltration (BF Goodrich Super Temp) to build up the density, then a 3000C graphitization to increase stiffness. The T-300 honeycomb webs did not see the graphitization step as it does not improve the material properties. The parts for the test models were machined and assembled with C-34 graphite cement. The assembled test models were instrumented with platinum thermocouples and the entire assembly was subjected to a second carbonization and carbon CVD. As a final processing step, the front facesheets were coated with silicon carbide to provide an oxidation resistant coating. Two SiC coatings were evaluated, a conventional carbon vapor infiltration SiC and a polymer precursor SiC conversion.



2a)



2b)

Figure 2a) Egg crate and 2b) Honeycomb core structures

The ARC JET TEST

The objective of this arc jet test was to verify the aeroshell structure and its materials can survive a simulated Mars entry and maintain backside heat output low enough for a spacecraft to survive until aeroshell separation. Specifically,

Table 1: Material Test Matrix

Composite Material List for Nonablative Aeroshell -- Optimized Model									
Models	Face plate (5" dia)			Core Structure (1" Hight)			Middle & Bottom Plate		
	Material	thknss	Layups	Material	thknss	Layups	Material	thknss	Layups
A1	2mil P30x(tape)	24	[0/+60/-60]2s	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
A2	2mil P30x(tape)	16	[0/+45/-45/90]s	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
A3	5mil XN50(fabric)	15	[0/45/0]	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
A4	5mil XN50(fabric)	20	[0/45/45/0]	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
B1	2mil P30x(tape)	24	[0/+60/-60]2s	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
B2	2mil P30x(tape)	16	[0/+45/-45/90]s	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
B3	5mil XN50(fabric)	15	[0/45/0]	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
B4	5mil XN50(fabric)	20	[0/45/45/0]	5mil T300 (fabric)	10 (H)	[+/-45]	2mil P30x(tape)	16	[0/+45/-45/90]s
C1	2mil P30x(tape)	24	[0/+60/-60]2s	2mil P30x(tape)	16 (E)	[0/+45/-45/90]s	2mil P30x(tape)	16	[0/+45/-45/90]s
C2	2mil P30x(tape)	16	[0/+45/-45/90]s	2mil P30x(tape)	16 (E)	[0/+45/-45/90]s	2mil P30x(tape)	16	[0/+45/-45/90]s
C3	5mil XN50(fabric)	15	[0/45/0]	2mil P30x(tape)	16 (E)	[0/+45/-45/90]s	2mil P30x(tape)	16	[0/+45/-45/90]s
C4	5mil XN50(fabric)	20	[0/45/45/0]	2mil P30x(tape)	16 (E)	[0/+45/-45/90]s	2mil P30x(tape)	16	[0/+45/-45/90]s

Note:
Thickness Unit: mil
HC: Honeycomb core
T300 (low K)
EC: (eggcrate core)

1) Verify the thermal performance of the proposed aeroshell models.
2) Verify the aeroshell structure coating and bonding design.
3) Measure temperature profiles of the front facesheet, internal interfaces and the rear facesheet of the aeroshell structure.
4) Evaluate the thermal .response of the aeroshell structure based on the test data.

The arc jet test runs were performed in the Interaction Heating Facility (IHF) of the Arc Jet Complex at Thermophysics Facilities Branch of NASA Ames Research Center, Moffett Field, CA, in April 19-20, 2000. The 60-MW Interaction Heating Facility was used to perform 6 runs on 4 C/C non-ablative models. Details regarding test facilities and the models can be found in the reference [6]. A summary of the test run conditions is presented in Table 2. The thermocouple locations are shown in Figure 3. Figure 4 shows an expanded view of the aeroshell test model in the ceramic holder.

Table 2. Arc Jet Test Run Conditions

Thermal Exposure (nominal)	Duration	Model Surface Pressure (mm Hg)
2900 F (40sec)	100 sec	40

*Note: During the cool down period chamber pressure is to be held as close as possible to run pressure; however, not to exceed the run pressure.

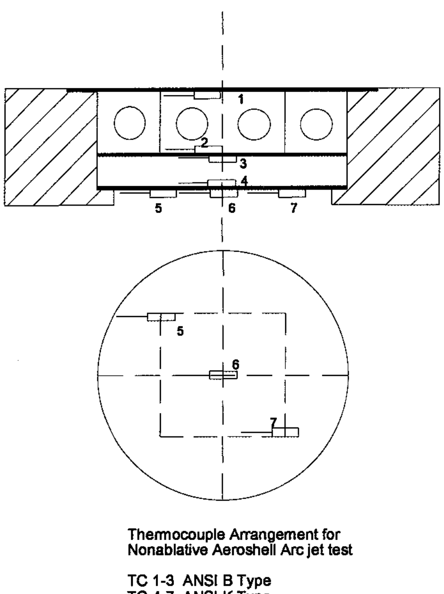


Figure 3. Location of the thermocouple during the arc jet tests and support of the test model in SIRCA insulation

The test procedure can be summarized as:

1. Start (Arc jet on).
2. Adjust arc heater parameters (current, mass flow, and model distance from nozzle exit) to the desired test conditions.
3. Swing in the calibration probe into arc jet for 40 seconds, then swing out of arc jet. Collect data at 20 Hz .
4. Conduct data sampling for at least 200 seconds after introduction into arc jet

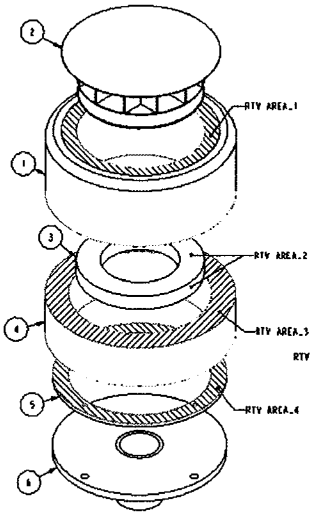


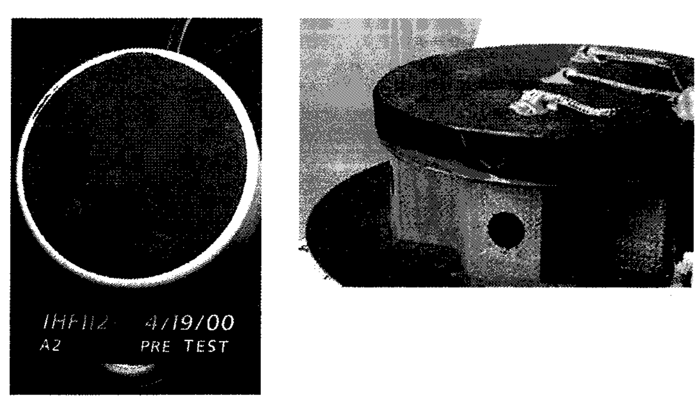
Figure 4: Expanded view of the test model in the ceramic holder

TEST MATRIX

Although all twelve of the test models were fabricated, only six were tested in the arc jet facility. This was due to limited availability of the facility. The models tested are listed in Table 3. This reduced set was representative of the untested design options. Figure 5 shows the A2 test model Prior to the test.

Table 3: Test models description tested in Arc Jet

Model #	SiC Coating	Core Type	Aerogel
A1	CVI	Honeycomb	RF/SiO2
A2	CVI	Honeycomb	Carbon
B2	Polymer	Honeycomb	Carbon
B3	Polymer	Honeycomb	Carbon
B4	Polymer	Honeycomb	Carbon
C3	CVI	Egg crate	Carbon



Test Model Test Model in Holder

Figure 5: View of an assembled test model.

ARC JET TEST RESULTS

Figure 6 shows the test model in the arc jet plasma flow. All six test models survived the tests with no visible degradation of the front surfaces. The SiC surfaces were discolored, due to reaction of contamination on the surfaces. Erosion of the surface was not measurable. For some of the runs, thermocouples failed to operate during part of the test. All of the test models maintained their thermal structural integrity during the test. When the test models were removed from the arc jet plasma and began cooling, the front face sheets debonded for several of the honeycomb core structures. This debonding was also observed during Phase 2 of this test program. The test model with the eggcrate core survived intact. The facesheet debonding is believed to be due to a gas buildup within the core structure that provided a positive internal pressure. This backpressure within the test model is a design consideration that must be taken into account in future scaleup of this technology. For the eggcrate core in this test matrix, tabs were machined into the core to provide mechanical interlock. There was minor but significant localized erosion at the tab.

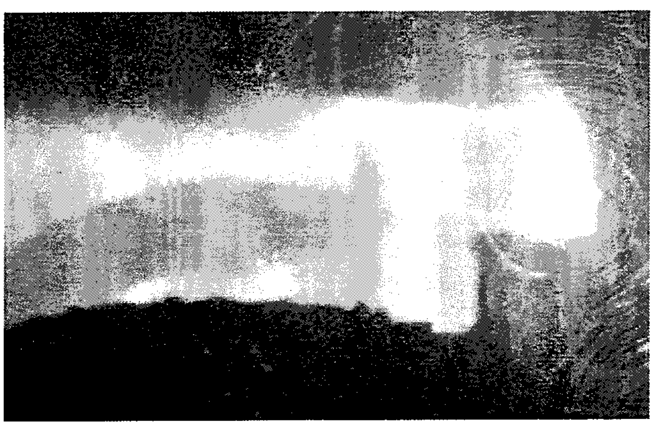
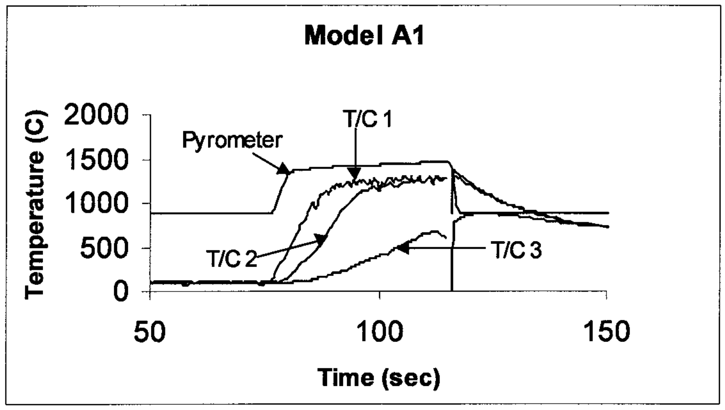


Figure 6: Picture the test model during the arc jet test

Figure 7 shows the temperature profile results obtained during the test of model A1. The shapes of the thermal profiles were similar in each of the six tests except in cases where the thermocouple failed and provided data with significant noise. Thermocouples 1-3 were the most prone to failure, with the cause of failure debonding due to thermal shock. The Pyrometer temperature represents the front surface temperature of the SiC coated carbon-carbon that is in the plasma flux. TC 1 measures the heat flux passing through the carbon-carbon facesheet. TC 2 measured the heat flux that passes through the core structure, and TC 3 measured the heat flux that passed through the middle facesheet. TC 4 measured the heat flux that passed through the carbon aerogel, and TC 5-7 measured the radial thermal profile on the rear facesheet.



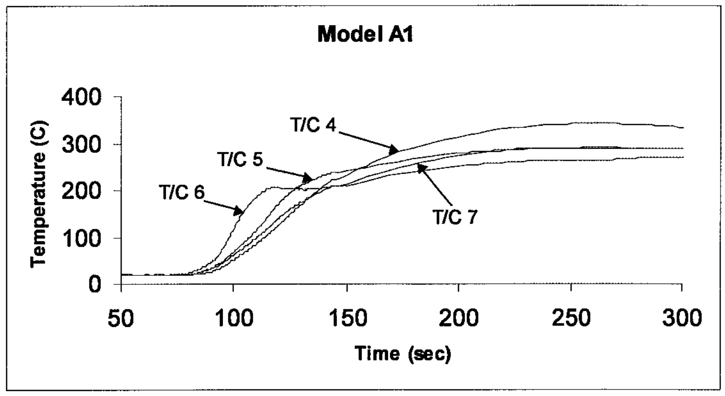


Figure 7: Arc Jet Test temperature profiles for model A1

Table 4 provides a summary of the thermocouple data for the surface pyrometer temperature, TC-1, 3 and 6 after 40 seconds and also TC-6 after 60 seconds. The atmospheric Entry and Decent sequence for a Mars is expected to last 40 seconds. The data for TC 6 at 60 seconds is to represent worst case thermal soak through.

Table 4. Selected temperatures in degrees Celsius during the Arc Jet Testing after 40 Seconds for TC 1,3,and 6 and 60 Seconds for TC-6.

Test Model	Pyrometer	TC-1	TC-3	TC-6 (40Sec)	TC-6 (60Sec)
A1	1480	1320	600	200	200
A2	1500	1400	400	140	170
B2	1470	1500	1070	150	183
B3	1515	1510	ND	200	250
B4	1520	1420	1225	275	305
C3	1470	ND	ND	140	150

ND: No data

Due to the nature of the data, it is difficult to make definitive conclusions. As expected, there was a modest thermal lag from the front facesheet to the center facesheet. As seen in the past work, there was the significant thermal lag passing through the carbon aerogel. The most significant difference between A1 and A2 was the type of aerogel. It is clear that the carbon aerogel performs better than the RF/SiO2. This is not an unexpected result since the vitrification temperature of the SiO2 aerogel in on the order of 1050° C. It is clear that the CVI SiC coatings performed better than the polymeric conversion SiC coating. Post test analysis will be conducted to determine if the effective emissivity has changed. Unfortunately, this can only be conducted at room temperature and not at the operating temperature. The one comparison between the honeycomb core and the eggcrate core showed no significant difference in thermal performance. One major conclusion that can be made is that the carbon aerogel provides significant thermal insulation in the simulated Mars entry environment at a level that would allow the survival of a payload.

CONCLUSION

Arc jet testing was conducted successfully at the Ames Research Center's Arc Jet Complex. The 60-MW Interaction Heating Facility was used to perform 6 runs on C/C non-ablating test models. The tests showed the viability of the carbon-carbon nonablative design, and the thermal performance of the carbon aerogel. The test objectives are met, even though some C/C facesheets did have debonding problems, by providing test data to verify the design and thermal performance of the Carbon-Carbon Non-ablating Aeroshell model. This test data can then be used in thermal structural modeling for large systems. The CVI SiC coating on the front face performed better than the polymeric SiC precursor coating. This work can serve as the basis for future work for advanced concepts for planetary entry thermal design solutions.

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