Arcjet Testing of Woven Carbon Cloth for Use on Adaptive Deployable Entry Placement Technology

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Abstract - **This paper describes arcjet testing and analysis that demonstrates the viability of three dimensional woven carbon cloth for multi-use in the Adaptive Deployable Entry Placement Technology (ADEPT). ADEPT is an umbrella-like entry system that is folded for stowage in the launch vehicle's shroud and deployed in space prior to reaching the atmospheric interface. A key feature of the ADEPT concept is a lower ballistic coefficient for delivery of a given payload than seen with conventional, rigid body entry systems. The benefits that accrue from the lower ballistic coefficient include factor-of-ten reductions of deceleration forces and entry heating. The former enables consideration of new classes of scientific instruments for solar system exploration while the latter enables the design of a more efficient thermal protection system. The carbon cloth now base lined for ADEPT has a multi-use in that it serves as the thermal protection system and as the "skin" that transfers aerodynamic deceleration loads to the umbrella-like substructure. The arcjet testing described in this paper was conducted for some of the higher heating conditions for a future Venus mission using the ADEPT concept, thereby showing that the carbon cloth can perform in a relevant entry environment. The testing and analysis reported here played a key role in achieving a major project milestone and was highly significant to the success and possible adoption of ADEPT for future NASA missions. Importantly, this paper also describes a preliminary engineering level code, based on the arcjet data, that can be used to estimate cloth thickness for future ADEPT missions and to predict carbon cloth performance in future arcjet tests.**

1. INTRODUCTION

Work on the Adaptive Deployable Entry Placement Technology (ADEPT) began in October 2011 and is funded by the NASA Headquarters Space Technology Program (STP), Game Changing Development Program. Figure 1 depicts the entry system for ADEPT that resembles an umbrella. The device is stowed for launch within the rocket's shroud and deployed in space, prior to atmospheric entry. This drawing is for an embodiment of ADEPT for a future mission that would deliver a Venus Intrepid Tessera Lander (VITaL) that is described elsewhere [1]. The inset shows the "skeleton" of the system in the stowed and deployed states. A major advantage of the ADEPT-VITaL entry system is that its reduced ballistic coefficient gives rise to deceleration forces ten times lower than a conventional rigid body capsule, thereby enabling the use of more capable scientific instruments for future solar system exploration. Further, the lower ballistic coefficient also enables deceleration to occur at higher altitudes with heating rates about ten times lower than those encountered by conventional rigid systems. This feature allows for consideration of a more efficient thermal protection system (TPS) for ADEPT, and was the reason for considering carbon cloth for this function.

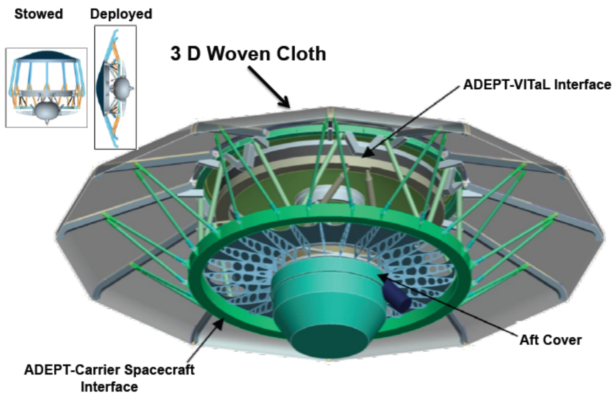

Figure 1. An entry system that employs ADEPT for the Venus Intrepid Tessera Lander Mission.

Also identified in Fig. 1 is the thin, multi-use 3 D woven carbon cloth that serves both as the TPS and the "skin" that transfers the aerodynamic deceleration forces to the ADEPT "skeleton". Remarkably, analysis of the arcjet test data has shown that the carbon cloth thickness required for the 6-meter base diameter entry system for the ADEPT-VITaL mission is only 0.38 cm.

The remainder of this report is organized into four main sections: (2) A brief description of the carbon cloth, (3) A discussion of the arcjet testing on 3 D woven carbon cloths at NASA Johnson Space Center (JSC) that is believed to the be the first of its nature to be published, (4) The carbon cloth weave down selection, and (5) Carbon cloth performance data and an engineering level code based on the arcjet data that can be used for preliminary thickness sizing for future ADEPT mission studies. These sections are followed by (6) Dual Heat Pulse Capability, (7) Conclusions and Summary (8) References, (9), Acknowledgements, and (10) Appendix A, Diffusion-Controlled Oxidation of Carbon.

2. Three Dimensional (3 D) Woven Carbon Cloth

Carbon cloth can be woven in many different ways and the weave architecture is a significant factor in how the fabric reacts to external, hot flows. The cloth tested at the NASA Johnson Space Center (JSC) was comprised of eight inter-woven layers and was 0.254 cm (0.10 in) thick. Four different weaves ("A", "B", "C" and "D") of the carbon cloth were arcjet tested to provide comparative performance data in the simulated entry environment. All four weaves are called 3 D woven because each features a 3 D interlock such that only one layer at a time is lost as the hot gases "burn" through the cloth. As expected, the differences in the weaves played a significant role in the response of each cloth in the simulated entry environment.

As can be seen from Fig. 1, the carbon cloth is only supported along the perimeter of each gore and is in bi-axial tensile loading during entry. Mechanical testing (tensile) of the carbon cloth revealed that for each weave, hysteresis was present but could be eliminated by cycling the cloth through several flight-like tensile loads prior to use for arcjet test articles. The cloth conditioning/tensile testing provided stress-strain curves to the ADEPT project for preliminary structural design activities.

3. Arcjet Testing

Arcjet testing was conducted at the NASA JSC Test Point 2 (TP2) facility during two entries, one in the fall of 2011 and the other in the spring of 2012. The TP2 arcjet is capable of producing ground simulations representative of atmospheric entry environments. For the present work, two entry conditions were chosen that fall at the mid-point and approaching the maximum for the ADEPT-VITaL mission, 136 W/cm^2 at 3.35 kPa pressure and 246 W/cm^2 at 9.6 kPa pressure, respectively. All arcjet testing discussed in this report used air as the test gas.

Figure 2 shows the arcjet test article. The cloth was held taut in a water-cooled copper wedge, and flush with the flat surface of the wedge. The arcjet flow impinged on the cloth and wedge surface at an angle of 37.5 degrees. The conditions quoted above correspond to the point where the heat flux and pressure were calibrated using sensors in a copper plate insert. The cloth was held in tension in the direction normal to the flow by a clamp and screw device shown in the cross sectional view in Fig. 2. Conditioned carbon cloths with hysteresis effects eliminated were used for the test article construction. To ensure that the cloth would not deform by the surface pressure from the arcjet flow, a mass simulating the pressure load was placed at the center of carbon cloth prior to testing. If the deflection was less than 2 mm, the test would not be compromised by small concavity and the resulting small change in heating as established by computational fluid dynamic (CFD) simulations. Again, the cloth for all tests at JSC was 0.254 cm (0.1 in) thick and was comprised of eight layers.

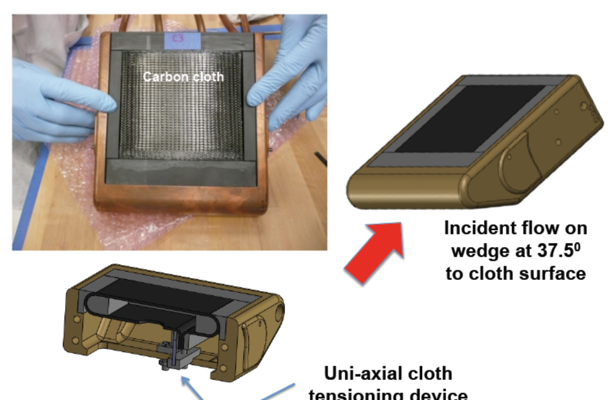

Figure 2. Photograph of the JSC copper wedge and sketches showing the carbon cloth drop-in unit and cloth tensioning device.

Critical instrumentation for the testing included: (1) high definition video of the flow over the wedge and the brilliantly glowing carbon cloth, (2) two pyrometers, one of which was looking at the station where the pressure and heat flux were calibrated while the other was measuring downstream temperatures, and (3) an IR camera focused on the carbon cloth and wedge surface and calibrated so that temperatures along the wedge centerline could be determined.

The Round 1 testing conducted in the fall of 2011 included two test article exposures on four different carbon cloth weaves at the TP2 "low" 136 W/cm^2, 3.35 kPa test condition. Key objectives of the Round 1 testing were to provide: (1) Evidence that 3 D woven cloth was viable for the multi-use ADEPT "skin" and (2) Relative performance of the four candidate weaves in a simulated and relevant entry environment. The first test article for each weave was kept in the arcjet flow until the cloth completely burned through all eight layers (dubbed "successful failure"), while the second exposure for each weave was extracted after 45 seconds. From these tests, it was determined that weave "A" exhibited superior comparative performance on the basis of controlled and uniform layer removal in the simulated entry environment. However, weave "A" exhibited relatively poorer mechanical properties in tensile testing for cloth conditioning. Weave "C", which exhibited better performance during tensile testing, performed poorly in the simulated entry environment. The other two weaves, "B" and "D", were composites with the top four layers exhibiting comparatively good aerothermal performance and the bottom four layers providing relatively good mechanical performance in tensile testing.

As clearly observed in the high definition and IR camera data, all four weaves exhibited uniform, yet different layer removal behavior during exposure to the arcjet stream. Individual tows were observed to lift and glow brightly as they thinned and broke from the oxidation caused by the hot flow. For the tests on the composite weaves to be "successful failures," high definition video provided times for the removal of the top four layers of the cloths that were used for the development of a preliminary thermal response model. (See Section 5).

The objectives of the Round 2 testing at NASA JSC were: (1) Compare relative aerothermal performance of the Super Weave A (SA) 3 D cloth to be base lined for ADEPT (described in section 4 below) to that from Round 1 testing and (2) Obtain performance data on Weave SA at conditions at the peak heating of the ADEPT-VITaL entry trajectory.

The first Round 2, control test was conducted at the 136 W/cm^2 and 3.35 kPa test condition on a 0.254 cm thick weave "A" test article. The second test was on weave SA at this condition. Weave SA performed as expected, and the time to burn through to the lower 4 layers was consistent with data for weaves "D" and "A". One test at the higher condition (246 W/cm^2 and 9.6 kPa) was obtained. Weave SA at the "high" condition run performed well. As expected, the upper four layers were removed at a faster rate due to harsher stream conditions.

4. WEAVE DOWN SELECTION

The information needed for the weave down selection was the relative mechanical performance during the cloth conditioning to remove hysteresis as well as the layer removal at the TP2 "low" condition of 136 W/cm^2 and 3.35 kPa. On the basis of these relative performance data, it was decided that weave "D" would be acceptable as a new baseline for the ADEPT project. However, plans for the project required carbon cloths in larger widths than those provided for the arcjet tests. Because the existing looms used by our partners at Bally Ribbon Mills, Bally PA could not produce weave "D" in the required widths, another, very similar weave, Super Weave A (SA) was selected for the baseline.

Based on the data collected from the NASA JSC Rounds 1 and 2 testing and the heat-load requirements anticipated for a Venus entry, the thickness of the baseline SA weave was increased by 50 percent by increasing the number of layers.

5. CARBON CLOTH PERFORMANCE AND PRELIMINARY ENGINEERING MODEL

As is becoming a standard "best practice" for arcjet testing, predictions from theory were used to guide the NASA JSC TP2 campaign. Unpublished CFD [2] by Larin for the expected flow conditions over the copper wedge was available. The TP2 calibration data supported these predictions. Co-author Laub used Larin's CFD and data as inputs to the Fully Implicit Ablation and Thermal (FIAT) code [3] to predict the carbon cloth recession prior to the commencement of the TP2 Round 1 entry. The FIAT modeling considered a "hypothetical" solid carbon film of density and thickness identical to that of the cloth. The predictions considered two types of oxidation:

(1) Diffusion-controlled and (2) Kinetics-controlled. The predicted recession assuming kinetics control was very slow compared to that for diffusion-controlled oxidation. Comparison of the measured time to remove the top 4 layers of the cloth to the FIAT prediction assuming diffusion-controlled oxidation showed that the test times were roughly half those predicted. Many reasons for this accelerated "recession" are possible. However, on the basis of the data gathered from the video and microstructual analysis on the samples, it was surmised that the primary reason for the difference in observed and predicted "recession" was that the cloth, being woven and fibrous, had more effective surface area than the hypothetical carbon film. Comparisons of the predicted surface temperatures (assuming a cloth emissivity of 0.9) of the cloth to the pyrometer data showed good agreement.

Study of the TP2 "high" condition (246 W/cm^2 at 9.6 kPa) also showed that the FIAT recession prediction was slow compared to the arcjet test results by roughly the same factor as that observed for the "low" test condition. This led to the conjecture that the FIAT code could be "anchored" to the arcjet test data and then used as a preliminary engineering level tool to predict carbon cloth layer removal for missions, and as a guide for the design of future arcjet tests.

The comparison of the TP2 test data (recession rate and surface temperature) at the "low" and "high" conditions to the FIAT predictions suggests that it is safe to assume, that for the arcjet tested conditions, diffusion-controlled oxidation is the dominant thermo-physical process. If this assumption is valid, the following should hold true regarding recession rates of the cloth: (1) Convective heat rate drives recession, and (2) Flow field pressure has very small effects on recession. The reasons for this are explained in Appendix A.

The discussion now focuses on a detailed comparison of FIAT predictions to the arcjet test performance data. The free stream predictions required for the wedge aerothermal performance (including the convective heat transfer coefficient discussed in Appendix A) were determined from CFD calculations of the arcjet nozzle flow field and sampling at the test location [4]. This is an approximation, but was deemed sufficient for the present comparisons.

FIAT has an option to run with a recession augmentation (RA) that accelerates the recession to correctly account for surface energy balance. Figures 3, 4 and 5 illustrate the comparisons of the FIAT predictions to arcjet data. The colored lines shown in Fig 3 in a "fan" shape correspond FIAT predictions of the cloth recession with a sweep of recession augmentations (RA). The RA values start at 1.2 and detent down by steps of 0.1, stopping at 0.7. Arcjet data for the recession halfway through the cloth were determined from careful inspection of the high definition videos and noting the time that the first appearance of the structural weave was exposed. Insertion time was referenced to the instant the test article was swung completely into the flow. These times are plotted with the red and black diamonds at a recession of 0.127 cm (0.05 in) as can be seen in Fig. 3 for the TP2 "low" condition. As can be seen from the plot, a recession augmentation of ~ 0.9 to 1.0 provides a correlation of the measurements, meaning that the carbon cloth recession is 1.9 to 2 times faster than that for the hypothetical solid carbon film (See Appendix A for the defining equation). The burn through (BT) time for weaves SA and D are comparable, as would be expected from their similar manufacture

Also shown on Fig. 3 is the comparison of the measured surface temperatures to the FIAT prediction assuming that the cloth emissivity is 0.9. The FIAT prediction is shown by the solid green line. Surface temperatures measured by pyrometery are shown by dashed lines (black for weave SA, red for weave D). The pyrometer data for the two runs lie nearly on top of each other, while the FIAT prediction is slightly lower than the measurement. Window losses were accounted for in the pyrometer data. The reason for the small difference between the FIAT prediction and the arcjet test data is not known, but the comparison is gratifying. It is possible that future measurements of the carbon cloth emissivity at elevated temperatures can improve the comparisons.

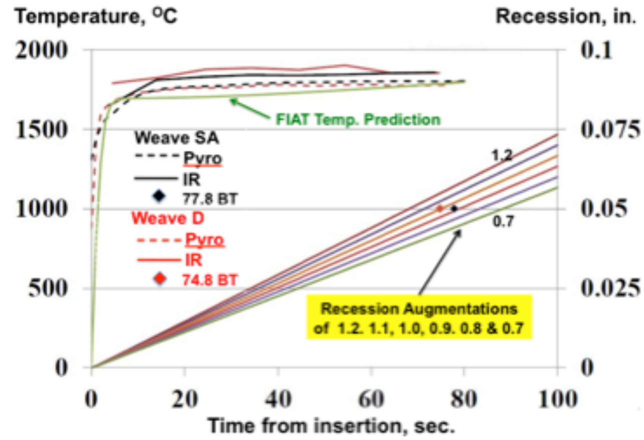

Figure 3. Comparison of arcjet data to FIAT predictions for the TP2 "low" condition of 136 W/cm² and 3.35 kPa. BT is the measured time in seconds to burn through to the upper four layers (or halfway through the cloth 0.05" or ~0.13 cm). Recession is read from the scale to the right of the plot, while temperature °C is read from the scale to the left.

The solid lines (black and red for weave SA and D, respectively) are temperatures determined from the calibrated IR camera. They correspond to a point along the wedge centerline, and also to the point where the calibration data mentioned above were obtained. As can be seen from inspection of Fig. 3, the IR camera data read ~ 100 °C higher than the pyrometer data. According to the JSC TP2 facility manager, the IR data always read about 100 °C higher than the pyrometers due to a scattered light issue.

Figure 4 shows arcjet data from the "high" TP2 test condition (246 W/cm^2 at 9.6 kPa). The format and symbols follow those used in Fig 3. For this condition, a recession augmentation of ~ 0.7 for FIAT correlates the test BT data. The pyrometer for this run was saturated, and so the data were not plotted on this figure. The IR temperatures shown by the solid black line are high compared to the FIAT prediction. Recalling that the temperatures read from the IR camera records read ~ 100 °C high, the comparison seems reasonable and in line with the data taken from the TP2 "low" condition.

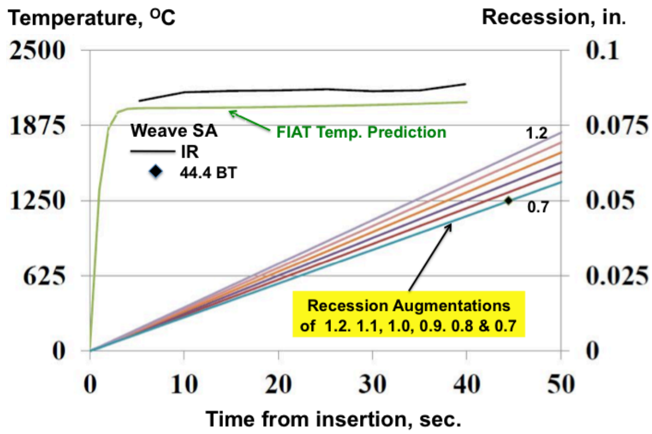

Figure 4. Comparison of TP2 arcjet data to FIAT predictions for the "high" condition (246 W/cm2 and 9.6 kPa).

Runs with the FIAT code were performed to evaluate the relationship of the uncertainty of the arcjet heat flux to the deduced recession augmentation. This analysis suggests that at 246 W/cm^2 and assuming that the true recession augmentation is 0.9, an uncertainty of +/- 10 percent in the heat flux results in a variation of RA from 1.1 to 0.75. It is estimated that the measured time for burn through for the top four layers has an uncertainty of plus or minus one second. Realizing that arcjet data normally exhibit scatter of +/- 10 percent or more, it is probable that a relatively large set of arcjet data will be required for a statistically significant determination of the recession augmentation for the carbon cloth layer removal. Pressure is not a significant factor in uncertainty provided that diffusion controlled oxidation is the dominant process in the testing.

The testing at NASA JSC discussed above was conducted with the cloth stretched in one direction (uni-axial). This work served as a precursor to bi-axial arcjet testing conducted in the NASA Ames Interaction Heating Facility (IHF) in July 2012 [5]. A major objective of the test campaign in the IHF was to determine the effects of layer removal by the arcjet stream while the cloth was held in flight-like, bi-axial tensile loading.

Figure 5 corresponds to a test in the IHF campaign [5] on a different wedge geometry, but where the heat flux of 137 W/cm^2 is nearly identical to those in the TP2 "low" test condition at 136 W/cm^2. The pressures are significantly different, with the IHF test at 9.1 kPa while those for the TP2 testing was 3.35 kPa. As discussed above and in Appendix A, if diffusion controlled oxidation dominates the thermophysics in the testing, pressure should have little effect on layer removal. The cloth thickness in the IHF tests was 0.38 cm (0.15 in) corresponding to 12 layers with the top 8 being sacrificial and the lower 4 providing structural stability. The formatting for the plot in Figure 5 is the same as in Figures 3 and 4, except the pyrometer data are plotted with a solid black line. For this IHF test, an augmentation factor of slightly less than 1.2 correlates the test data, and the FIAT predicted surface temperatures are in close agreement with the pyrometer data (better than that observed in the TP2 data).

It is interesting that the deduced recession augmentations for the two runs are close (0.9 to 1.0 for the TP2 test compared to ~ 1.2 for the IHF test). While it is understood that <u>many</u> factors could complicate the comparison of the data (uni-axial versus bi-axial loading, differences in cloth thicknesses, density, pressure, etc) to that from the IHF tests, it is noteworthy that the two runs from different facilities seem to be reasonably well correlated by FIAT operating with the recession augmentation. Further, the FIAT correlation for nearly identical heat rates and widely differing pressures (3.35 kPa versus 9.1 kPa) suggests that diffusion controlled oxidation is dominant at these test conditions.

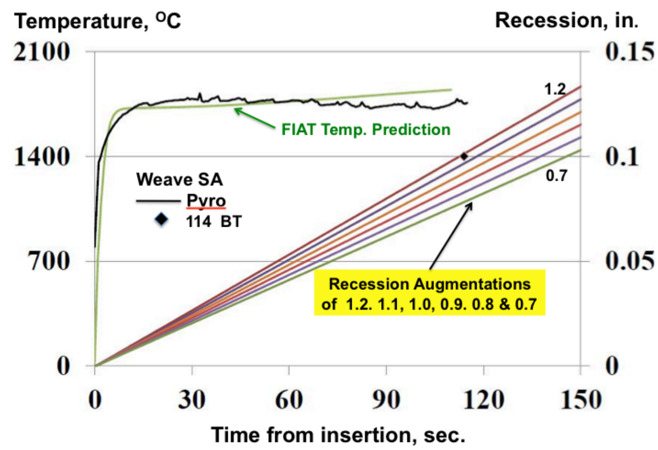

Figure 5. Data from reference [5] presented here pre-publication, with approval from the authors. The test conditions are 137 W/cm^2 and 9.1 kPa. Note that the weave SA cloth here is 12 layers thick, and burn through (BT) is specified for the time to burn through 8 layers or 0.10 inches (0.245 cm) and the pyrometer data are plotted with a solid black line.

While it is understood that there is **<u>very limited</u>** arcjet data to compare to the FIAT predictions, it seems safe to say that this code run with the recession augmentation of 0.9 +/- 0.2 comes close to correlating the carbon cloth layer removal arcjet data presented here. It is the intent of the authors to analyze all of the IHF data to be presented in [5] and other future results to see if this correlation holds, and hopefully reduce the recommended spread of recession augmentations for future use.

Importantly, it should be noted that the post TP2 arcjet tested articles have been analyzed for microstructural effects caused by exposure to the arcjet stream. The findings [6] show that tow and fiber thinning/sharpening and breakage is observed in the first structural layer that was in direct contact with the arcjet stream, but that those on the bottom (four layers underneath) were **not** affected as compared to a non-arcjet-tested sample that was conditioned as described in Section 2. This suggests that hot oxygen was not significantly flowing completely through the carbon cloth in the TP2 tests. Sharpening of carbon-carbon has been observed in other flows with diffusion-controlled oxidation, as seen in reinforced carbon-carbon debris recovered from the Shuttle Columbia accident [7].

6. DUAL HEAT PULSE CAPABILITY

As discussed in [8,9], Aerocapture is considered to be enabling for human missions to Mars and to trade well against the use of rertro-propulsion in terms of mass savings for many missions [10]. Aerocapture using a 23 m diameter ADEPT requires a dual heat-pulse capability of 110 W/cm^2 for aerocapture, followed by out-of-orbit heating rate of 30 W/cm^2.

During the second entry at JSC, there were two runs that aborted because the arc heater automatic safety shut-off system was activated. A decision was made to not pull the test article from the stream but to simply restart the facility and test to "successful failure' with second application of the heating. The run conditions for both tests SA2 and SA3 were 210 $W.cm^2$ at a pressure of 9.58 kPa. Importantly this shows that the 3 D woven carbon fabric can endure dual heating. As can be seen from Table 1, the run times appear to be consistent and demonstrate that dual heat pulse capability beyond that for the human Mars mission seems achievable.

Table 1 Record of run times for arc heater abort cases
Entry times are in seconds that the arcjet was running

Time to:	SA 2	SA3
Abort	30	24
Burn Through	39	38
Total Run	69	62

7. CONCLUSIONS AND SUMMARY

The arcjet testing and analysis discussed in this report documents information that, when combined with performance data from arcjet tests [5] on carbon cloth when under flight-like bi-axial loading, has retired the risk that 3 D woven carbon cloth might not be able to provide a multi-use (TPS and a "skin" that transfers deceleration loads to the substructure) for ADEPT. The results of the NASA JSC testing and analysis were used by the ADEPT project to down select to a 3 D Super Weave A (SA) carbon cloth that is now base lined for the project. These results go far in advancing the technology readiness level of ADEPT and its potential adoption for future NASA missions.

Analysis of the arcjet data and comparisons to FIAT predictions for a hypothetical carbon film using the option for recession augmentation of 0.90 +/- 0.2 seem to be capable of correlating the limited arcjet test data presented. It appears that for the tested conditions, diffusion limited oxidation dominates the recession rate. Future work should include more comparison of FIAT predictions to arcjet data to verify that diffusion controlled oxidation dominates the thermophysics for the flight envelope, and to provide improved bounds on the recession augmentations. Furthermore, arcjet testing in CO_2 should be compared to FIAT run with B' curves for Venus' atmosphere. FIAT is widely used for sizing of conventional TPS for a given trajectory e.g. the Orion AVCOAT TPS and phenolic impregnated carbon ablator (PICA) for Stardust and Mars Science Laboratory. It seems safe to say that, if used in the mode with bounded recession augmentation determined from arcjet testing on carbon cloth, FIAT could be used for preliminary sizing of the thickness of the "skin" for the ADEPT-VITaL mission.

The microstructural observations of the post TP2 arcjet tested 3 D carbon cloth suggest that thinning by oxidation did not persist through four layers of the cloth at flight-relevant conditions. This suggests that four layers in the carbon cloth could be a sufficient margin for flight designs.

Finally, the two runs that suffered from the automated arc heater shut down with re-starts demonstrated that the carbon cloth is capable of dual heat pulse operation, important for missions that utilize aerocapture and subsequent out-of-orbit entry.

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9. APPENDIX A. DIFFUSION CONTROLLED OXIDATION OF CARBON

For diffusion-controlled oxidation, B'_c is fixed at a constant value (0.176 for air), which is independent of surface pressure and temperature (see Figure A 1 below). B' is defined as a non-dimensional mass flux. Thus, surface recession solely depends on convective heat transfer coefficient, which is the ratio of convective heat flux and recovery enthalpy. The recession rate = $(1 + RA) \times B'_c \times C_H/\rho$ where RA is Recession Augmentation factor, C_H is convective heat transfer coefficient (equal to the convective heat rate divided by the difference of the edge enthalpy and the wall enthalpy) and ρ is the density.

It is believed that the density that should be used for FIAT modeling is that which the cloth will exhibit when in flight-like bi-axial tensile loading. These data are not yet available and for the interim, it is believed that the thicknesses determined by BRM using the ASTM standard should be employed, namely 0.254 cm (0.1 in) for the 8-layer cloth and 0.381 cm (0.15 in) for the 12-layer cloth. Using the BRM thicknesses and measured masses of a rectangular piece of cloth, the density for the 8-layer cloth is ~ 0.95 g/cc and that for the 12-layer cloth is ~ 0.92 g/cc.

9. ACKNOWLEDGEMENTS

The authors recognize that this report could not be written without th8e help and dedication of many individuals. First, we express our gratitude to Dr. Keith Peterson for the use of data for Fig 5, obtained in the NASA Ames testing on carbon cloth to be published in reference [5] and to Dr. Parul Agrawal for the discussion on the microstructual analysis included herein pre-publication [6]. We note the very significant contributions to the arcjet test article design and construction by Sergey Gorbunov. Others from NASA Ames who supported the design and construction of the arcjet models include Dan Empey, Mairead Stackpoole, Don Ebaugh and Dan Rozewitch. The testing at NASA JSC could not have been done without the support of Steven Del Papa, and his superb support crew including Tien Nguyen, David Williamson, Bryan Kanne and Sandy Davis. Finally, we appreciate the efforts of Nancy Mangini to prepare this manuscript.

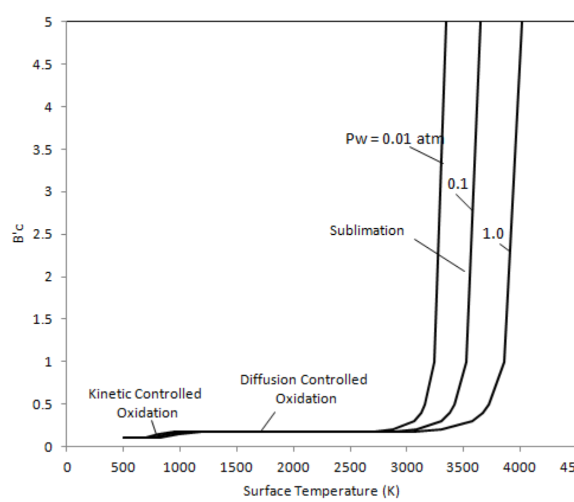

Figure A1. B' versus surface temperature for carbon in air.