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 has successfully demonstrated the viability of three dimensional woven carbon cloth for dual 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 its lower ballistic coefficient for delivery of a given payload than those for 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 dual use in that it serves as ADEPT's thermal protection system and as the "skin" that transfers aerodynamic deceleration loads to its 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 ADEPT project considered the carbon cloth to be mission enabling and was carrying it as a major risk during Fiscal Year 2012. The testing and analysis reported here played a major role in retiring that risk and is highly significant to the success and possible adoption of ADEPT for future NASA missions. Finally, this paper also describes a preliminary engineering level code, based on the arcjet data, that can be used to estimate cloth thickness for future missions using ADEPT and to predict carbon cloth performance in future arcjet tests.**

TABLE OF CONTENTS

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 Division. Figure 1 depicts the entry system for ADEPT that has similarity to a patio 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, 2]. The inset shows the "skeleton" of the umbrella-like system in the stowed and deployed states. A major advantage of the ADEPT-VITaL entry system compared to a conventional rigid body capsule is that its reduced ballistic coefficient gives rise to deceleration forces ten times lower 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 reductions also about ten times lower that the conventional rigid systems. This allows for consideration of more a efficient thermal protection system (TPS) for ADEPT and this was the reason for considering carbon cloth for this function.

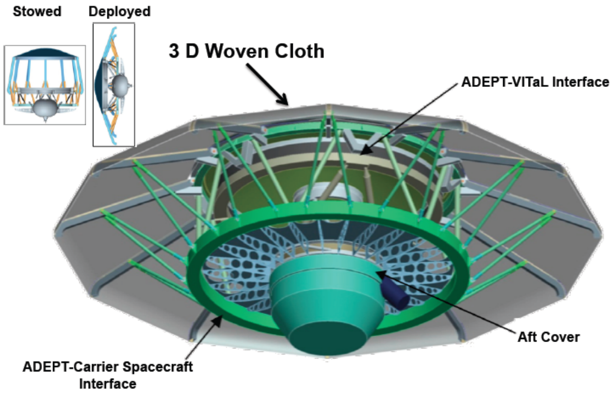

Figure 1. An entry system that embodies ADEPT for the Venus Intrepid Tessera Lander Mission

Also identified in Fig. 1 is the thin, dual use 3 D woven carbon cloth that serves both as the TPS and the “skin” that transfers the aerodynamic deceleration forces to ADEPT’s “skeleton”. Remarkably, as will be discussed below, analysis of the arcjet test data presented herein has shown that the carbon cloth thickness for the 6 meter base diameter entry system for the ADEPT-VITaL mission is only 0.38 cm.

This report is organized into four main sections: (2) A brief description of the carbon cloth that is consistent with its being considered an International Traffic in Arms Regulation (ITAR) protected technology and that the detail of its manufacture is considered to be proprietary by our partners Bally Ribbon Mills, Bally PA. (3) A discussion of the arcjet testing on 3 D woven carbon cloths at NASA Johnson 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 a first order 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) Conclusions, (7) References, (8), Acknowledgements, (9) Biographies and (10) Appendix A, Diffusion controlled Oxidation of Carbon.

2. THREE DIMENSIONAL (3 D) WOVEN CARBON CLOTH

Again, details of the carbon cloth weave and its constituents are restricted by ITAR controls and specification of the weave is BRM propriety. The carbon cloth can be woven in many different ways and the weave architecture has a significant role as to 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 were 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 in the simulated entry environment. All four weaves are called 3 D woven because each feature 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 terms of the response 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. This hysteresis was 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 Johnson Space Center Test Point 2 (TP2) facility during two entries, one in the fall of 2011 and the other in the spring of 2012. The TP2 facility is capable of producing ground simulations representative of atmospheric entry environments. For the present work, two conditions were chosen that fall at the mid point and approaching the maximum for the ADEPT-VITaL mission namely 136 W/cm^2 at 3.35 kPa pressure and 246 W/cm^2 at 9.6 kPa pressure, respectively.

Figure 2 depicts 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 their 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 so measured 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 thickness for all tests at JSC was 0.254 cm (0.1 in) and was comprised of eight layers.

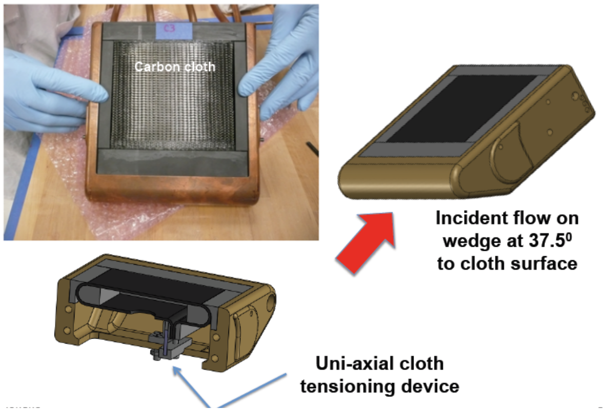

Figure 2. Photograph of the JSC copper wedge and sketches showing the carbon cloth drop-in unit and cloth tensioning device

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. This IR camera is calibrated such that temperatures along the wedge centerline could be determined.

The resolution of the high definition videos is good enough that one can deduce the weave patterns in stills that are considered ITAR and proprietary to our partners Bally Ribbon Mills. Consequently no images extracted from the high definition video or IR movies will be shown herein.

Ellerby comment: "I don't think you need this paragraph. Anyways I would think you could show the stills. BRMs key IP is how they make a particular weave which just showing a still image isn't going to reveal. But going down this path then we could never show a still image of a weave, even non arcjet tested. However, As I (Jim) interpret Raj's direction, clearly we should not show images, either videos or stills We need to get on the same page and be consistent into the future"

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. The first test article 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 for both weaves "B" and "D" 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 could be observed to lift and glow brightly as they thinned and broke from the oxidation caused by the hot flow. For the tests to "successful failure" on the composite weaves, 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 to be discussed in section 5 below.

The Round 2 testing in TP2 was intended to bridge the results of the Round 1 weave down select testing into arcjet testing on that to be base lined for ADEPT and called Weave Super A {(SA) - see section 4 below}. Testing on SA was conducted both at JSC and in the NASA Ames Interactive Heating (IHF) facility. The first TP2, 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 necessary 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. Plans for the project required carbon cloths in larger widths than those for those provided for the arcjet tests. The current looms at BRM could not produce weave "D" in those widths so another, very similar one, was selected for the baseline. It is called Super Weave A or SA for a short acronym.

Based on the data collected from TP2 round 1 and 2 testing and the heat-load requirements anticipated for a Venus entry, the thickness of the base line 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 TP2 campaign. Unpublished CFD [3] 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 [4] 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 thermophysics: (1) Diffusion controlled oxidation 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 gleaned from the video and microstructual analysis on the samples to be discussed below, it was surmised that the primary reason for the difference in observed and predicted "recession" is that being woven and fibrous, the cloth has more effective surface area than the hypothetical carbon film. Comparisons of the predicted surface temperatures (assuming an emissivity of 0.9) of the cloth to the pyrometer data showed good agreement.

Study of the TP2 "high" condition (246 W/cm2 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 an 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 true, the following should hold regarding recession rates of the cloth: (1) Convective heat rate drives the recession, and (2) Flow field pressure will have very small effects on the 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 freestream predictions required for the wedge aerothermal performance were determined from CFD calculations of the arcjet nozzle flowfield and sampling at the test location [5]. This is an approximation, but was deemed sufficient for the present comparisons.

As it turns out, FIAT has an option to run with a recession augmentation (RA) that accelerates the recession correctly accounting for surface energy balance. Figures 3, 4 and 5 illustrate the comparisons of the FIAT predictions to arcjet data. The colored lines shown 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. It is estimated that the measured time for burn through the top four layers has an uncertainty of plus or minus one second. These times are plotted with the red and black diamonds at a recession of 0.127 cm (0.05in) as can be seen in the data 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. A recession augmentation of 0.9 to 1.0 means that the carbon cloth recession is 1.9 to 2 times faster than for the hypothetical solid carbon film (see Appendix A). The burn through (BT) times for weaves SA and D are comparable, as would be expected from their similar manufacture. 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 suggest 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. Realizing that arcjet data normally exhibit scatter of +/- 10 percent or more, it may be 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. Uncertainty in pressure is not a player in uncertainty if the belief that diffusion controlled oxidation is the dominant process in the testing.

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. The surface temperatures obtained by pyrometery are shown by dotted lines (black for weave SA while that for weave D is shown in red). The pyrometer data for the two runs lie nearly on top of each other, while the FIAT prediction is slightly lower than the measurement. 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.

The solid lines (red and black for weave D and SA, respectively) are temperatures read 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 ^{O}C higher than the pyrometer data. According to the JSC TP2 facility manager, the IR data always read about 100 ^{O}C higher than the pyrometers due to a scattered light issue.

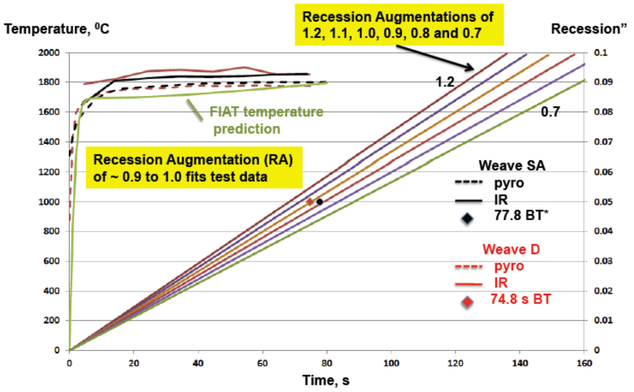

Figure 3. Comparison of TP2 arcjet data to FIAT predictions for the TP2 low condition of 136 W/cm^2 and 3.35 kPa. BT is the measured time in seconds to burn through to the upper four layers (or halfway through the cloth 0.05" or ~0.13 cm). Recession in inches, to be read to the scale to the right of the plot, while surface temperature ^{O}C is to be read from the scale to the left.

Figure 4 is 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 ^{O}C high, the comparison seems reasonable and in line with the data taken from the TP2 "low" condition.

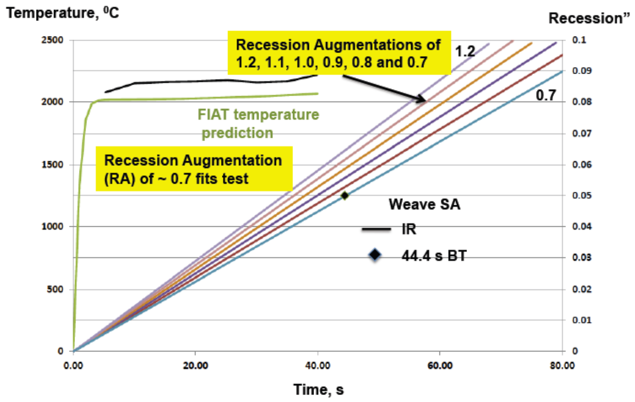

Figure 4: Comparison of TP2 arcjet data to FIAT predictions for the "high" condition.

The TP2 testing discussed above was conducted with the cloth stretched in one direction (uni-directional). This work served as a precursor to bi-axial arcjet testing conducted in the NASA Ames Interaction Facility (IHF) in July 2012 [6]. into the TP2 Round 2 and IHF testing on weave SA. A major objective of the test campaign in the NASA Ames 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 [6] 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 at 11.6 kPa while those for the TP2 test was 3.35 kPa. As discussed above and in Appendix A, if the dominant thermophysics is diffusion controlled oxidation, pressure will 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 is as in Figures 3 and 4 except here the pyrometer data are plotted with a solid black line. Here we see that, for the IHF test, an augmentation factor of slightly less than 1.2 correlates the test data, and that the FIAT predicted surface temperatures are in close agreement with the pyrometer data, better than observed in the TP2 data.

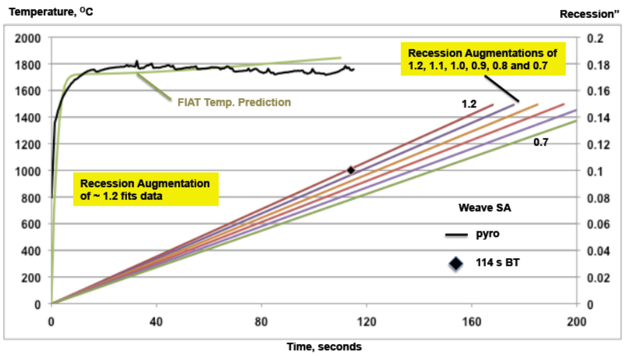

Figure 5: Data from reference [6] is presented here pre-publication, with approval from the authors. The test conditions are quoted in the text. Note that the weave SA cloth here is 12 layers thick and burn through is specified for the time to burn through 8 layers or 0.10 inches (.254 cm). Here, pyrometer data are plotted with a solid black line.

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 many factors could complicate the comparison of the TP2 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 option.

While it is understood that there is **very limited** 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 [6] and other future results to see if this correlation holds, and hopefully reduce the recommended spread of recession augmentations for future use.

Finally, 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 [7] show that tow and fiber thinning/sharpening and breakage is observed in the first 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 the 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 [8].

6. CONCLUSIONS AND SUMMARY

The arcjet testing and analysis reported herein documents information that, when combined with performance data from arcjet tests on carbon cloth when under flight-like bi-axial loading, has retired the risk that 3 D carbon cloth might not be able to provide a dual use (TPS and a "skin" that transfers deceleration loads to the substructure) for ADEPT. The results presented herein were used by the ADEPT project to down select to a 3 D Super Weave A (SA) 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.

The reported arcjet conditions fall at the mid and near the upper limits of heat rates for the ADEPT-VITaL, so future testing should be conducted at the lower bounds for this mission to ensure that data will be available for design. If other ADEPT missions would encounter higher or lower heating rates, tests should be conducted for those conditions as well.

Analysis of the arcjet data and comparisons to FIAT predictions for a hypothetical carbon film using the option for recession augmentation of 9.0 +/- 0.2 seem to be capable of correlating the limited test data presented. It appears that for the tested conditions, diffusion limited oxidation dominates the recession rate. Future work should include more comparison of arcjet data to the FIAT predictions with the hope that improved bounds on the recession augmentations could be specified. FIAT is widely used for sizing of conventional TPS for a given trajectory e.g. the Apollo 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 to size the thickness of the "skin" for the ADEPT-VITaL mission.

Finally, the microstructural observations of the post TP2 arecjet 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.

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8. ACKNOWLEDGEMENTS

The authors recognize that this report could not be written without the help and dedication of many individuals. First, we express our gratitude to Dr. Keith Peterson for the use of data for Fig 5. from NASA Ames testing on carbon cloth to be published in reference [6]. We note the very significant contributions from NASA Ames in the design and construction of the arcjet models. This includes Sergey Gorbunov, Dan Empey, Mairead Stackpoole, Don Ebaugh

and Dan Rozewitch. The testing could not have been done at JSC without the expert help 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.

9. BIOGRAPHIES

***Dr. James O. Arnold** received his B.S. in Engineering Physics from the University of Kansas in 1962, his M.S. From Stanford in Aeronautics and Astronautics in 1967 and his Ph. D in Molecular Physics from York University Toronto in 1972. He has been affiliated with NASA for five decades and retired from the position of Chief of the Space Technology Division in 2002. He has worked for the University of California, Santa Cruz for the last 10 years. His technical experience is broad, spanning aerothermodynamics, TPS, theoretical spectroscopy and computational chemistry. His experimental research involved shock tubes, ballistic ranges and arcjets. He served at the branch and division level management levels for NASA for 20 years. His career began with work on the Apollo Program and he is a Fellow of the AIAA.*

***Dr. Yih-Kanq** Chen Received his Ph. D. in Mechanical Engineering from the University of Texas at Austin in 1989. He has been working for NASA for over 20 years. In his career, he developed the Fully Implicit Ablation and Thermal Response code (FIAT), and other Thermal Protection System material simulation tools.*

Bernard Laub (get his picture from the IPPW 2 tutorial

I'll provide

Mr. Laub received his B.S. in 1961 and his M.S. in 1963 from NYU and is widely known as one of the world leaders in the area of ablative thermal protection systems (TPS). His experience traces back to the development of AVCOAT for Apollo's TPS. As he worked in industry following Apollo, Mr. Laub managed testing and modeling of more advanced TPS materials. He led the development of methodology to model IR signatures from ballistic targets from launch to impact and was also responsible for defining the philosophy and methodology for testing of high-energy lasers for the Strategic Defense Initiative program. In recent years, Mr. Laub was brought to NASA to lead in the re-establishment of the agency's adaptabilities in research and development for ablative TPS. For this work, he received NASA's Distinguished Service Medal in 2008 and was selected for the AIAA Thermophysics award in 2012.

***Dinesh Prabhu** is a Senior Staff Scientist with ERC, Inc., an onsite contractor at NASA Ames Research Center. He received his B.Tech. in Aeronautical Engineering from the Indian Institute of Technology at Madras, India, and his Ph.D. in Aerospace Engineering from the Iowa State University at Ames, Iowa. His interests are in modeling and simulation of high-temperature hypersonic flow fields (for ground testing and flight), and in aerothermodynamic design of atmospheric entry*

***Molly Bittner** is currently an undergraduate at Georgia Tech, graduating December 2012 with a B.S. in Aerospace Engineering. She is a contractor with ERC, Incorporated performing work for NASA Ames Research Center following a Summer 2012 internship. She is conducting configuration studies for the ADEPT structure with a parametric mass model in MATLAB that she created during the summer internship. She also works as a research assistant in the Space Systems Design Lab (SSDL) at Georgia Tech under Dr. Robert Braun and graduate student mentor Juan Cruz. She is creating mass models for new parawing* *entry systems.*

. ***Ethiraj Venkatapathy*** *is currently the Chief Technologist for the Entry Systems and Technology Division at NASA Ames Research Center. He received his B.Tech. in Aeronautical Engineering from the Indian Institute of Technology Madras, India, and his Ph.D. in Aerospace Engineering from the Iowa State University at Ames, Iowa. He is currently leading the technology development efforts, as the PI for the Conformable and Flexible Thermal Protection System (CFA-TPS), the mechanically deployable semi-rigid ADEPT project and Woven Thermal Protection System (WTPS) project.*

10. 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 nondimensional mass flux. Thus, surface recession solely depends on convective heat transfer coefficient, which is the ratio of convective heat flux and recovery enthalpy.

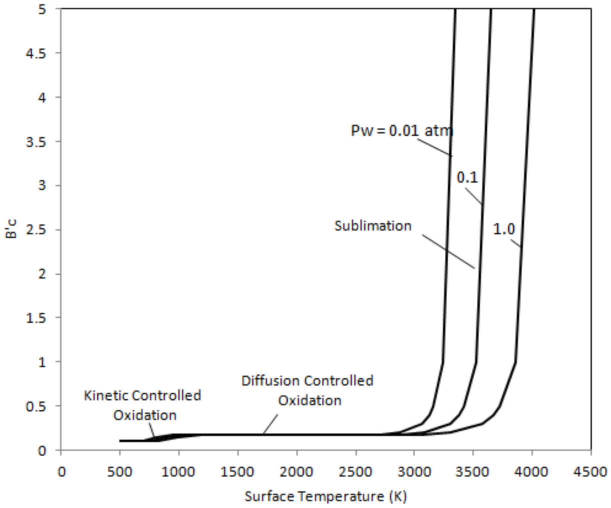

Figure A1. B' versus surface temperature for carbon.

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, 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.