

Validation and Sensitivity Analyses of Arc-Jet Performance of Woven Thermal Protection Entry Systems

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A material response model is developed for the determination of erosion rates and thermal response of woven materials to enable accurate thermal protection material sizing and future missions to Venus and giant planets. The stagnation-point thermal response is further evaluated using a Monte Carlo global sensitivity analysis to determine the interactions between key parameters in the material surface energy balance, such as, convective blowing correction parameter and weave material properties including isotropic and orthotropic thermal conductivities. The time-accurate material response for the dual layer weave erosion and surface temperatures show excellent agreement with stagnation flat face arc-jet tests involving time-varying aeroheating-cooling cycles. The high-fidelity Monte Carlo sensitivity analysis technique was used to address challenges in thermal protection sizing for the Adaptive Deployable Entry and Placement Technology (ADEPT) system, a low ballistic coefficient hypersonic decelerator. The results represent new correlations for such weaves involving Carbon-air oxidation equilibrium chemistry. Through the multi-variate regression analyses and uncertainty rankings performed, only three properties were found to contribute to the transient thermal response of the gore, with emissivity contributing to nearly 95% of the total output uncertainty.

I. Nomenclature

ρ	=	density, kg/m ³
c_p	=	specific heat, J/kg. K
T	=	temperature. K
t	=	time, s
$\mathbf{K}$	=	thermal conductivity tensor, W/m.K
u	=	velocity of surrounding air, m/s
C_h	=	Stanton number for heat transfer
C_H	=	Heat transfer coefficient in mass units, kg/s.m ²
H_r	=	recovery enthalpy, J/kg
h	=	enthalpy, J/kg
α	=	surface absorptivity
q_r	=	radiative heat flux, W/m ²
q_c	=	conductive heat flux, W/m ²
σ	=	Stefan-Boltzmann constant, W/m ² .K ⁴
ϵ	=	surface emissivity
$\dot{m}$	=	mass loss rate per unit area, kg/m ² .s
λ	=	blowing correction parameter

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Subscripts

c = carbon
 e = boundary layer edge
 w = wall/surface

II. Introduction

THE Adaptive, Deployable, Entry and Placement Technology (ADEPT) system is an umbrella-like decelerator system that is deployed prior to atmospheric entry. This system, which utilizes a woven carbon fabric with an ablative nose cap, has been the subject of study and experimental testing for the past decade. Past efforts have focused on establishing the feasibility of the woven configuration as an entry system by experimental interrogation in arc jets for typical "low" and "high" arc-jet test conditions [1, 2]. These woven materials have improved functionality over uniform heat shield materials [3] with the 3D weave technology offering potential shear resistance, enhanced durability and mass savings. In addition, the carbon fabric offers volume savings that allow for the inclusion of a secondary payload, such as in the Small Innovation Missions for Planetary Exploration (SIMPLEx) program [4]. The optimization of the weave technology and performance would enable future space missions, and development could be accelerated through suitable modeling efforts.

The initial validity of any model developed to characterize the performance of the ADEPT weave relies on accurate validations with arc-jet tests. In this regard, validations of test performance of a class of woven materials were performed using a one-dimensional [5], and more recently, three-dimensional Fully Implicit Ablation and Thermal response (FIAT) code [6, 7]. The numerical validation efforts typically involved simulation of flat-faced cylinder tests where in-depth temperatures were compared to thermocouple recordings. In addition to validating thermocouple data, material response modeling can also be used to characterize the performance of the weaves when subject to heating that has convective and radiative heating contributions. Validations of entire woven systems including acreage and seams rely on aerothermal and material response modeling efforts. In addition, modeling of the acreage and seams helps simulate more accurately the performance of the heat shield to typical re-entry conditions, including shock heating and re-attachment of the boundary layer at regions of high structural variation. Such validation efforts, however, have been fairly limited for ADEPT. For this reason, this work targets characterizing the material and thermal response of a dual weave fabric, and validating against arc-jet tests for flat-faced articles. The modeling approach used here helps simulate internal thermal response of materials subject to various conditions using isotropic and orthotropic conductivities for the heat shield material. The finite volume material response code can compute erosion rates and handle time-varying boundary conditions.

Beyond validation efforts, thermal protection system (TPS) margins require adjustments based on manufacturer specifications of material properties and atmospheric conditions to improve predicted performance of the woven material. Both of these, i.e. fiber properties and environments, have inherent uncertainties in them. Previous high-fidelity sensitivity and uncertainty analyses have focused on applications involving aerothermal non-equilibrium reaction rates [8] at the entry vehicle stagnation point for Titan aerocapture, and for afterbody radiative heating [9] of the Stardust capsule. The results demonstrated the relative importance of various reactions by considering thermodynamics, flow chemistry, and radiation. These studies would need to be complemented by similar analyses for TPS materials to help sizing efforts.

In one of the first studies involving sensitivities of material properties, Congdon [10] executed a Mars pathfinder mission sensitivity study for heat shield design based on arc-jet tests at NASA Ames Research Center. By accounting for varying nominal uncertainties in surface heat of ablation, convective blowing, pyrolysis char density and pyrolysis gas heat capacity, a corner-point sensitivity analysis was used to describe effects of heat shield ablation on bondline temperatures. In another study, material property uncertainties were incorporated in inverse reconstruction of time-varying surface heating of the PICA ablator [11]. The choice of the recession model was found to affect the inverse temperature predictions of thermocouples. More recently, a simplistic sensitivity analysis [12], and a more detailed sensitivity analysis of the VISTA ablator material database using Bayesian statistical inference [13], have demonstrated that virgin and char thermal conductivities were dominant contributors in charring ablation problems. A clear understanding of the extensibility of these results to non-pyrolyzing materials remains to be established and verified.

In the present work, a global Monte Carlo sensitivity analysis approach is used with a sufficiently large input space/sample size to characterize the performance of the weaves with respect to the convective blowing effects and

inherent material properties. This approach helps determine the interactions between various non-linear parameters and characterize the correlation to thermal response. Section III of the document describes the model used to capture erosion effects, Section IV demonstrates the validation results with flat-faced arc-jet tests performed at NASA Ames Research Center, and finally, global sensitivity analysis applied to the weave is detailed in Section V. The methodology presented here can be used to modify the material design to improve the performance of woven heat shields to suit mission and sizing needs.

III. Modeling and Constitutive Relations

The process to simulate the woven cloth consists of a two-weave formulation, with variations in properties between the two ablative weaves. The upper layer is simulated with isotropic conductivity, while the lower layer has orthotropic conductivity included. This is elucidated in the diagram shown below. Modeling of the woven heat shield material was

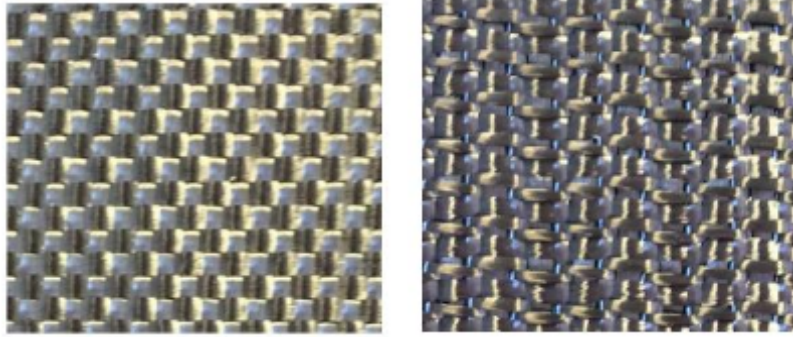


Fig. 1 Plain (left) and ortho (right) weaves that comprise the front and aft surface respectively of the carbon fabric stack-ups [14]

performed by solving the mass conservation equation and the following internal energy balance equation:

$$\rho c_p \frac{\partial T}{\partial t} - \nabla \cdot (\mathbf{K} \cdot \nabla T) = 0. \quad (1)$$

The fabric density and thermal properties are specified as functions of temperature, pressure and fiber orientation. The following surface energy balance equation helps address the interface of the aerothermal environment with the woven material:

$$\rho_e u_e C_h [H_r - h_w] + \dot{m} [h_c - h_w] + \alpha_w q_{rw} - \sigma \epsilon_w (T_w - T_\infty)^4 - q_{cond} = 0 \quad (2)$$

The heat transfer coefficient, wall and recovery enthalpies are obtained through computational fluid dynamics simulations. Typically, for arc-jet tests, laminar flow conditions are assumed to compute these values. Radiative and convective heating components, which are determined through test conditions, help compute the time-dependent temperature history of the internal energy of the fabric. The surface energy balance equation provides the necessary thermal and material response of the fabric.

A. Fiber mass loss computation with Lagrangian meshes

Fiber layer loss is an important parameter to determine sizing of the thermal protection system. In the simulations performed here, fiber mass loss is computed using B' tables through the following relation:

$$\dot{m} = B' * C_H \quad (3)$$

The finite volume solver used in this study has the ability to simulate and capture mesh movement with surface erosion mechanisms by using radial basis interpolation functions to compute new nodal positions. In order to prevent large distortion of the volume mesh, the Wendland C2 radial kernel which requires the solution to a sparse matrix system, is used. This methodology is used to compute material recession to track mass loss.

B. Convective blowing correction parameter

The conventional use of blowing reduction parameters to compute convective heat transfer to the material is incorporated in to code through the B' and C_H terms. The blowing correction, λ , is utilized in the following manner:

$$B' = \exp((2\lambda B'_1) - 1)/(2\lambda) \quad (4)$$

$$C_H = \log(1 + 2\lambda B') * \frac{C_{H,1}}{2\lambda B'} \quad (5)$$

The subscripts 1 in the above set of equations represent the unblown values of the parameters. For nominal values involving laminar flows, a lambda value of 0.5 is used. A bias to lower values would indicate transition to turbulent flow regime at the surface. This blowing correction would play a role due to mass loss and the resulting changes in the boundary layer due to fiber oxidation. The influence of this blowing reduction parameter on the thermal response of the woven material is discussed further in Section V.

C. Carbon-oxidation chemistry

Carbon fiber oxidation has an impact on the thermal and material response, and is activated through the B' and wall enthalpy terms. Equilibrium chemistry products are determined at the surface through the MUTATION++ [15] equilibrium solver. The input B' and h_w tables are interpolated by using binary search techniques for a specified temperature. With the arc-jet facility pressures remaining constant throughout the duration of the heating phase, this technique provides the necessary temperature-dependent values at select pressures. The equilibrium composition and respective product enthalpies are shown in Figure 2 as functions of temperature. The inclusion of a wall enthalpy term

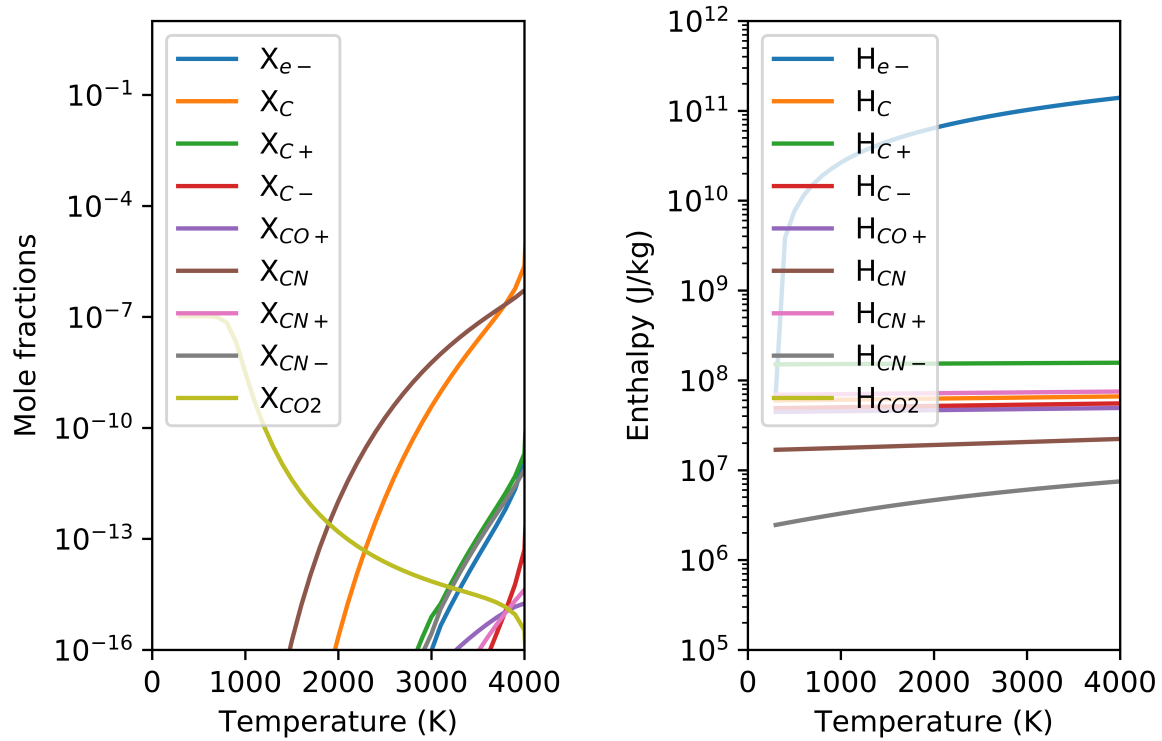


Fig. 2 Carbon oxidation equilibrium composition and major species enthalpies at 8.2 kPa pressure

that encompasses erosion effects adds a dimension of complexity to the thermal response of a time-varying aeroheating environment. The various terms in the surface-energy balance equation are therefore not linearly additive, and form a system whose behavior may not be easily discernible in unsteady conditions.

IV. Results and Validations

Arc-jet tests of the ADEPT carbon fabric were conducted with a flat-face stagnation model geometry in the Aerodynamic Heating Facility with a 45.72 cm (18 in) diameter conical nozzle (AHF344) at the facility's maximum heating condition. The test articles, one of which is illustrated in Figure 3, comprised a 27.69 cm (10.9 in) diameter LI-2200 holder that closed out a 15.29 cm x 14.00cm (6.02 in x 5.51 in) tensioned carbon cloth sample. The carbon fabric consisted of eight upper layers of plain weave and four lower layers of ortho weave and has been tested in a previous arc-jet test campaign [2]. Test articles were positioned 31.12 cm (12.25 in) downstream of the nozzle exit and exposed to a cold-wall, stagnation-point heating of $\sim 95\text{W/cm}^2$ for a duration of 60 s. The flat-face test articles were designed to provide uniform heating across the surface area of the fabric. Four samples were subject to these tests to observe experimental variability in peak heating and mass loss for the same conditions. The front surface temperature was measured using a two color pyrometer, and the aft surface was measured using two different thermocouples placed at the center of the sample (R-type) and diagonally offset by 1.05 inches from the center (C-type). In addition, post-test recession measurements were made to determine the layer loss to the sample.

The aerothermal conditions determined using the Data Parallel Line Relaxation (DPLR) solver [16] for the facility conditions, were input in to the present code, Icarus [17], to solve for the surface heating predictions and mass loss. An initial temperature of 300 K was used for the simulations. The recovery enthalpy and heat transfer coefficient contribute significantly to the thermal and material response of the upper weave due to a large convective heating component. Figure 4 shows the upper surface heating and cooling predictions with experimental pyrometer data. The peak heating temperature values are within 1% of experimental results with equilibrium surface chemistry inputs. Contrarily, the back face of the carbon fabric weave is treated to be radiating to the surrounding air in the arc-jet test facility. The back face shows some variability with different thermocouple data (Figure 5), and the prediction was within 20% of the R-type thermocouple (the one aligned at the center of the test surface) used in the test. The R-type thermocouple used a ceramic adhesive coating.

The material recession with time is depicted in Figure 6. This compares well with the experimental data and

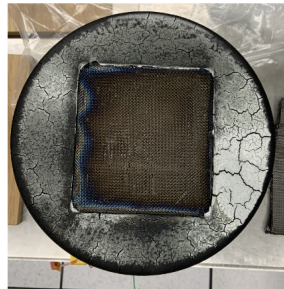


Fig. 3 Flat-faced stagnation test article of ADEPT weave in Aerodynamic Heating Facility (AHF) [18]

is in close agreement with post-test caliper measurements without the need for any C_H -based scaling. It should be noted that caliper measurements were deemed more reliable than other in-situ recession measurements as the fabric is mounted with tension on the LI-2200 cylindrical holders, and any real-time recession measurements would likely involve additional contributions from the fabric tension. With the validation of the material response solver, it was of interest to determine the response of the material to parameters that can be controlled during weave fabrication and test design.

3D-weave characteristics that can be modified by the manufacturer include fiber thickness and number of layers in the acreage fabric. A simple parametric study of differential fiber thicknesses for the dual layers (Figure 7) traditionally used for such weaves shows no appreciable difference in the thermal response of the fabric. On a similar note, the variation in the total number of layers of the weave resulted in small ($< 50\text{ K}$) differences at the back face. Total stack height proved to be more valuable in controlling the overall thermal response of the weave than individual fiber/layer variations. This result is demonstrated in Figure 8. This is an important outcome as it has implications to the scale at

which modeling and properties such as thermal conductivity would be essential for such engineering applications.

Another simplistic variation that can be made to the environment, is to examine the effect of surrounding temperature at the back face of the sample. No appreciable variations (Figure 9) can be observed at the back face until significant atmospheric heating occurs. However, arc-jet tests do not typically record such high gas temperatures for this to be an important consideration. The parametric variations described herein can be made for simple variables, but do not allow for complex sensitivity analyses to be performed on multiple variables. A more intensive numerical process would need to be carried out in order to perform such analyses, as described in the following section.

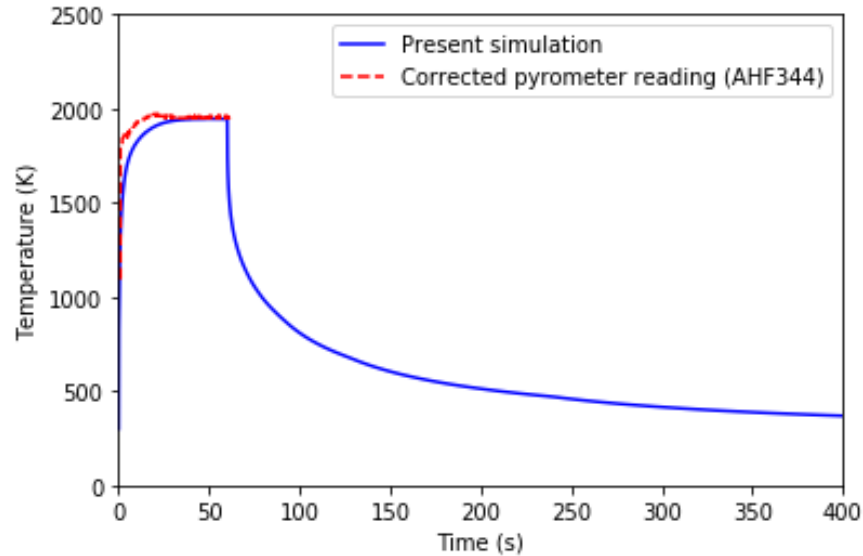


Fig. 4 Validation of the thermal response of the fabric front-face with pyrometer data for the Aerodynamic Heating Facility (AHF) test. The experimental result corresponds to a sample exposure time of 60s, measured peak wall heat flux of 232 W/cm^2 , and a pressure of 8.2 kPa (Experimental test reference number: SN001).

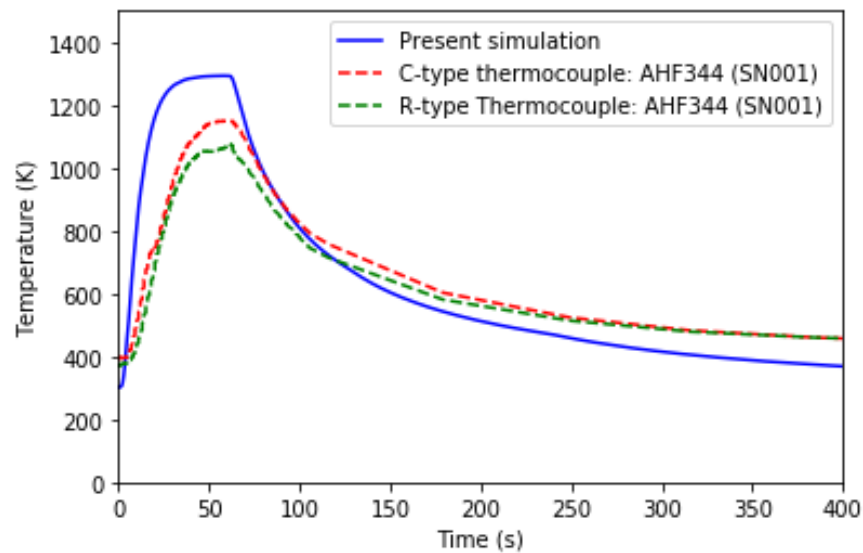


Fig. 5 Comparison of thermal response of the back face of the fabric with thermocouple measurements for the Aerodynamic Heating Facility (AHF) test

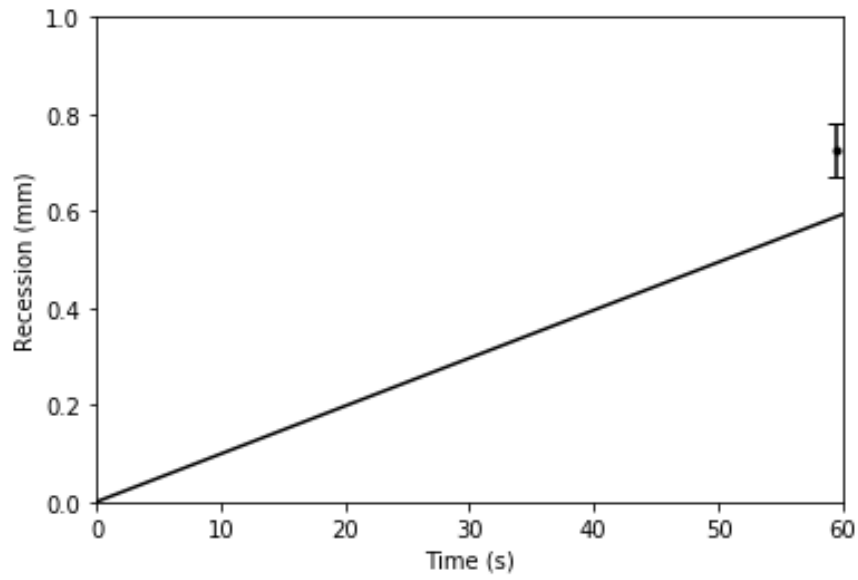


Fig. 6 Carbon fabric recession due to erosion for the Aerodynamic Heating Facility (AHF) test

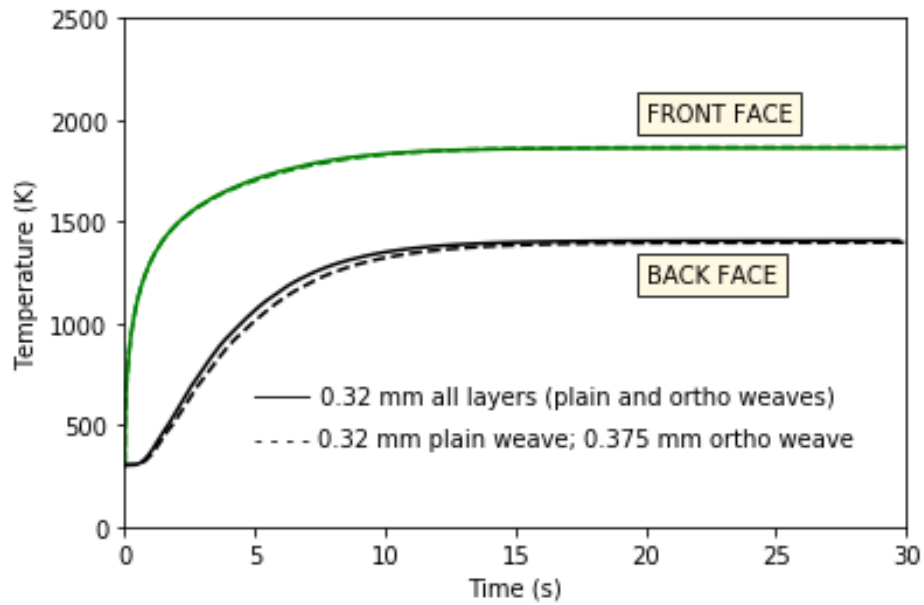


Fig. 7 Effects of variation in per-layer fiber thickness between plain and ortho weaves on thermal response

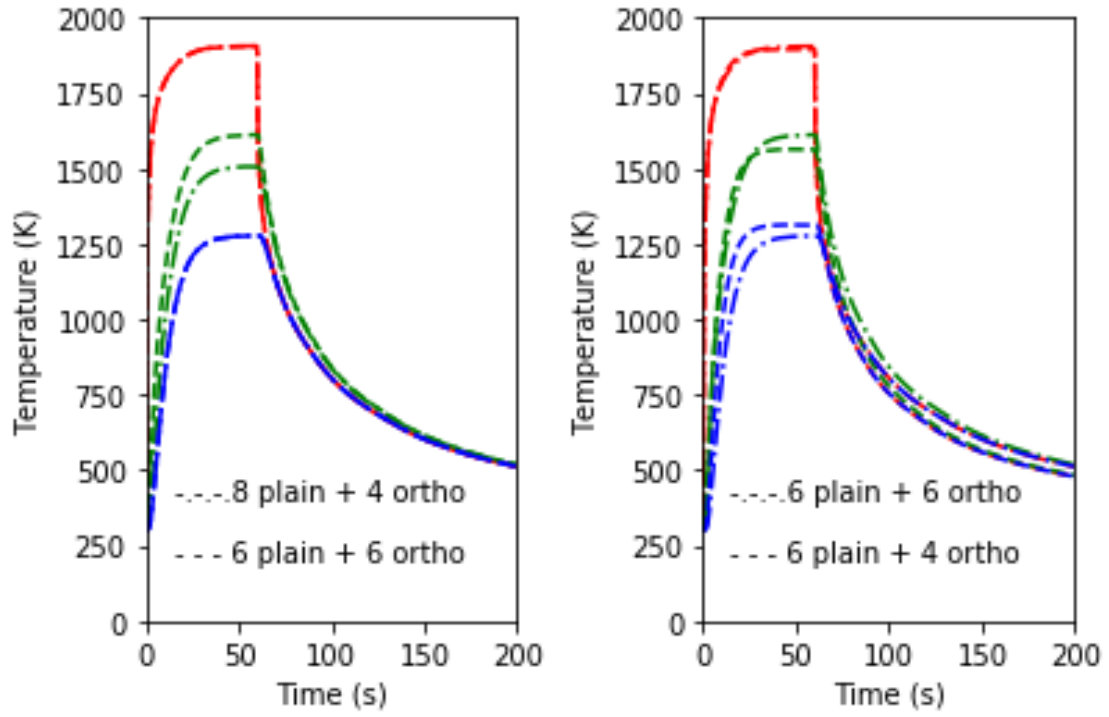


Fig. 8 Effects of weave stack height on thermal response (■: Front plain-weave surface; ■: Interface of plain and ortho weaves; ■: Aft ortho-weave surface)

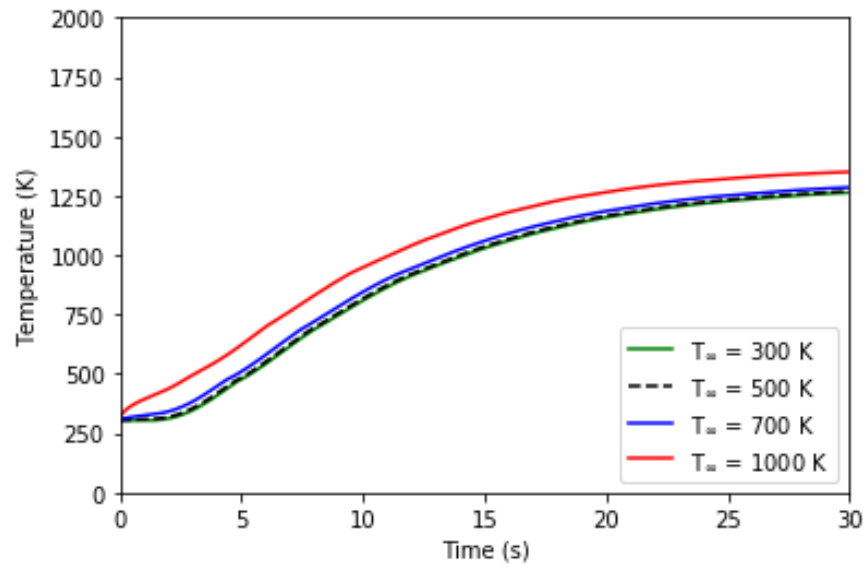


Fig. 9 Thermal response of back face of the carbon fabric to surrounding facility temperatures

V. Sensitivity Analyses

The fabric response may be sensitive to parameters intrinsic to the material or external to it due to the flow conditions during tests. The choice of the methodology to be used for sensitivity analyses depends on the relevant parameters of interest and how they interact to make up the system response. Local sensitivity analysis is applicable to parameters that scale linearly or that do not interact with each other. It can be applied to determine the sensitivity of the fabric for easily differentiable governing equations. This type of analysis is suitable for small deviations in a parameter from its nominal value, and is best suited for analytical methods where a finite difference method is feasible. Alternatively, a numerical one-at-a-time sensitivity analysis can also be performed for local variations of parameters and for simple functions without large computational overheads. However, with the inclusion of non-linear equilibrium chemistry effects, this methodology does not lead to tractable solutions. In addition, if a large variation is desired in the study space, such local analyses do not provide the necessary fabric sensitivities.

A. Global Sensitivity and Uncertainty Ranking

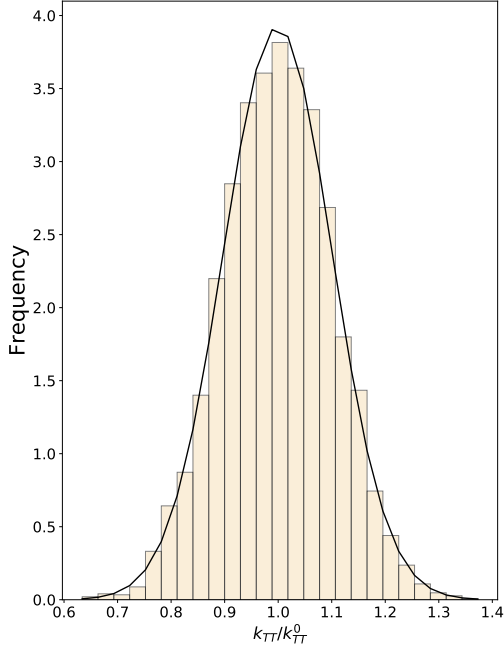
In order to quantify the sensitivity of the woven fabric system to several fabric properties and surface blowing factors, a Monte Carlo analysis was performed to determine the thermal response. The methodology involved determining the initial parameters of interest and their ranges for random sampling during the Monte Carlo simulations. These are depicted in Table 1. The smaller variances on some of the parameters were made to ensure that ranges are limited to theoretically possible values. The Monte Carlo analysis allows for independent random variation of each of the parameters, and provides the combined system response to such values.

In this study, Gaussian distributions were assumed for the variables and random samples generated for each of the chosen 7 variables. The probability distributions for a sample input, and combinatorial system peak thermal output are shown in Figures 10a and 10b respectively. Such a probability distribution function has similar inherent assumptions of associated uncertainties. It is also assumed that there are no correlations in the inherent material property uncertainties or the assumed blowing parameter. It should be noted that for any random sample generated, a uniform uncertainty was assumed to propagate through the entire temperature range for properties that were strong functions of temperature, such as thermal conductivity and specific heat. The random samples were generated for the inputs based on this assumed probability distribution function. For each such combination, the weave temperatures were recorded. As shown in Figure 10b, the binned temperature output was slightly skewed to values below the nominal peak temperature. It was observed that a total of 5000 simulations were sufficient to generate converged solutions. This process included a time-dependent temperature history for the dual-weave stack.

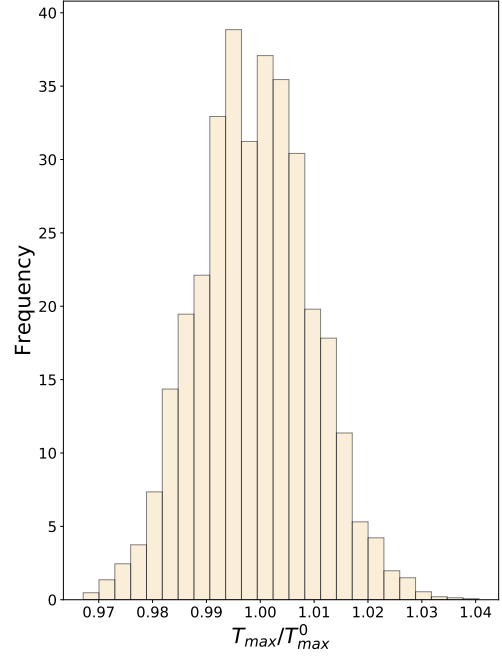
Surface temperature data for the time-varying simulations were then used to generate correlation data for the various parameters. This is observed in the scatter plots shown in Figure 11 at 20s of the aeroheating cycle, and in Figure 12 at steady-state response to peak operation of the arc-jet test facility. The normalized peak heating temperature at the surface of the fabric shows weak or no correlation with blowing correction parameters, in-plane conductivity, absorptivities and specific heats. However, through-thickness conductivity shows a weak negative correlation with peak temperature, and emissivity is highly negatively correlated with temperature. When intermediate temperature correlations are observed in the time-varying heating profiles, slightly different results are observed, with smaller negative correlations for some of the variables (Figure 11), and specific heat showing a non-trivial correlation to thermal response in transient heating conditions.

Table 1 Ranges chosen for global Monte Carlo sensitivity analysis

Parameter	% variation of nominal value
Blowing correction	± 10
Through-thickness thermal conductivity	± 4
In-plane thermal conductivity	± 4
Emissivity	± 5
Absorptivity	± 5
Specific heat	± 10



(a) Histogram of random samples used to represent through-thickness conductivity of ADEPT weave. k_{TT}^0 represents the mean values provided by the manufacturer over a temperature range.



(b) Histogram of surface temperature at steady state heating over 5000 randomly sampled weave properties. This output response involves random sampling of all input variables provided in Table 1.

Fig. 10 Histogram of input-output sample distributions

The linear regression analysis performed on the data obtained provides for an approximate picture of the contributions of various parameters to fabric temperature uncertainty. The square of the correlation coefficient for the various parameters depicts the individual contributions to total output uncertainty. The contributions for transient and steady-state heating of the weave are shown in Figure 13. A striking consequence of the Monte Carlo sensitivity analysis and uncertainty ranking is that the emissivity of the fabric is the largest contributor to the uncertainty in thermal response of the fabric, and much larger than the contributions of constituent thermal conductivities. The thermal conductivities themselves contribute minimally ($\sim 2\%$) to the total uncertainty.

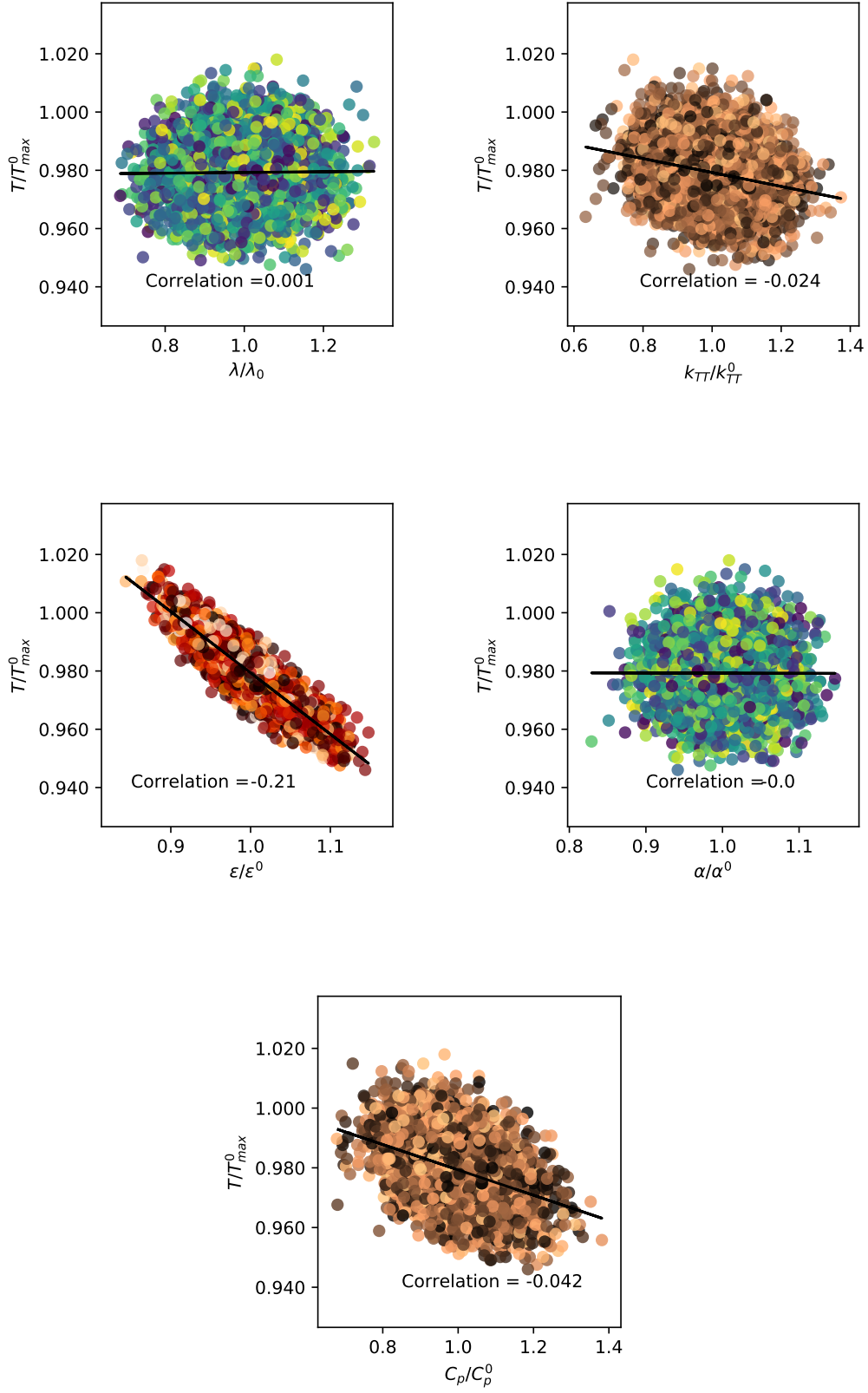


Fig. 11 Scatter plots depicting the correlation of surface temperature with blowing factor and material properties for the dual weave carbon fabric at 20s after initiation of the simulation

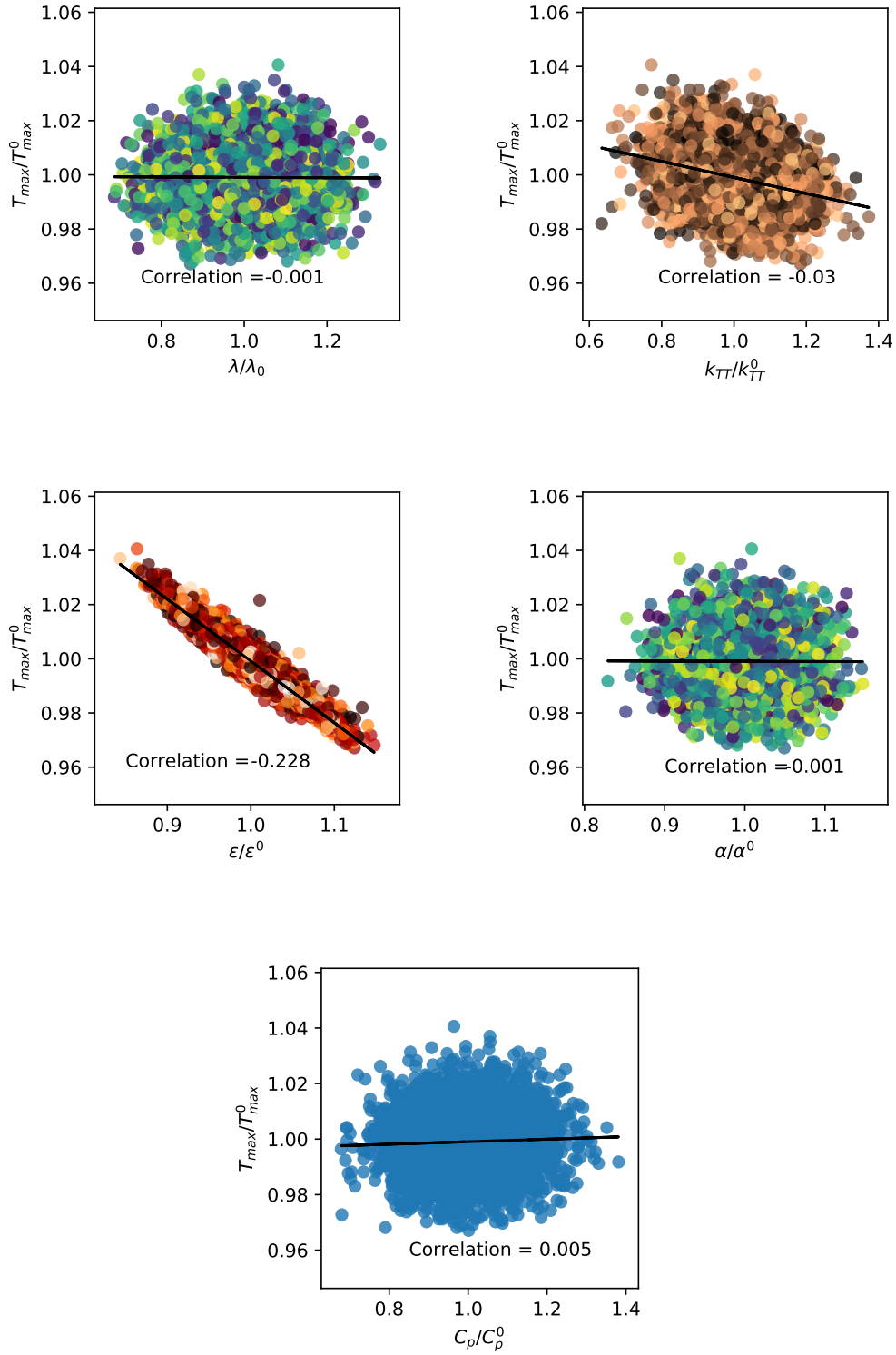


Fig. 12 Scatter plots depicting the correlation of surface temperature with blowing factor and material properties for the dual layer carbon fabric. The mean values are representative of steady-state conditions during peak operation of the arc-jet test facility.

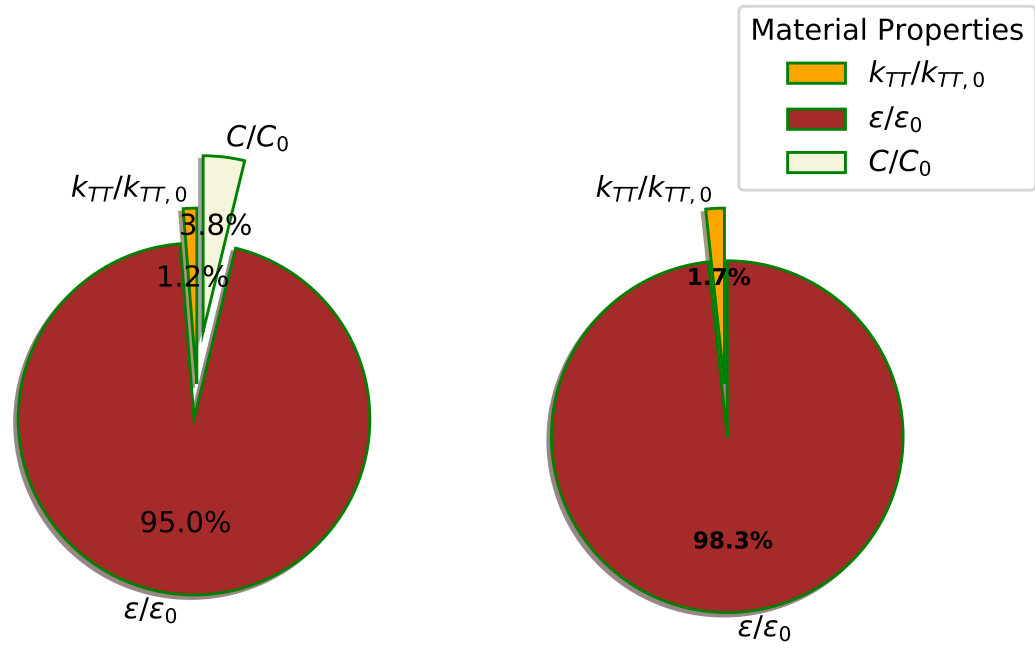


Fig. 13 Uncertainty ranking and distribution of critical parameters for transient (left) and steady-state (right) surface heating

VI. Conclusions

Woven thermal protection systems have the potential to sustain higher aerothermal loads than traditional tiled heatshield systems. Previous efforts on experimental testing have focused on woven materials stitched at seams and multiple layers on ribs. However, such a configuration leads to structural, aerothermal, and certification limitations for flight qualification. In lieu of the SPRITE model, a single-piece, 3-D woven, Spiderweave heatshield configuration is currently being pursued for flight test qualification and modeling. The ADEPT system has relied on one- and three-dimensional modeling to validate performance during arc-jet tests conducted in the past. Bondline temperature, surface temperature predictions and thermocouple validations are typically of interest for such modeling. The modeling and validation efforts typically involved scaled heat transfer coefficients and recession augmentation factors to obtain good agreement with experimental results.

In this effort, characterization of the woven material thermal response for arc-jet conditions in a dual-weave acreage configuration is performed using a multi-dimensional implicit finite volume material response solver. The erosion model implemented was validated with a flat-faced cylindrical stagnation test performed at the Aerodynamic Heating Facility at NASA Ames Research Center. The effective treatment of mixed convective-radiative boundary conditions is demonstrated through close agreement of front- and back-face temperatures with experimental pyrometer and thermocouple data. Furthermore, a global Monte Carlo sensitivity analysis of the woven fabric to measured material properties and boundary layer blowing factors due to erosion was performed on the acreage configuration. Uncertainty ranking of the weave thermal response due to assumed Gaussian uncertainties in parameters revealed that fabric emissivity, conductivity, and specific heat of the carbon fabric were the only critical properties for thermal response accuracy. Furthermore, emissivity proved to be the single largest contributor to fabric temperature uncertainty at all times in the time-varying heating phase of the arc-jet tests. The fiber property sensitivities determined in the study could be utilized to qualify the performance of the multi-dimensional woven system for such unsteady boundary conditions, with re-evaluation of sensitivities for the required conditions.

Acknowledgments

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