15th Ablation Workshop

Nov 18–20, 2025

New Mexico State University

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BOOK OF ABSTRACTS

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15th Ablation Workshop

Nov 18–20, 2025

New Mexico State University, Las Cruces, New Mexico, USA

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Posters

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Validation of Multiphysics Ablation Modeling Simulation Capability: Comparison to Arc Jet Data for High-Temperature Materials Subject to Combined Environments

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This presentation focuses on the correlation of multiphysics simulations corresponding to a high-enthalpy ground test campaigns conducted at the NASA Ames Research Center Interaction Heating Facility (IHF). The aerothermal environment for hypersonic flight vehicles is severe and can generate extremely high material temperatures. These high-temperature environments can cause intense localized heating, which may result in local pockets and/or structural instabilities, especially at vehicle leading-edge regions, and may affect vehicle performance. The aerothermal environment may also amplify the damage induced by transient localized heating caused by a variety of sources. At sufficient velocities, these profile disruptions may affect the structural integrity or vehicle trajectory with disastrous consequences. ATA Engineering, Inc. (ATA), has developed a fluid-structure-material interaction (FSMI) software toolset that incorporates mutual interactions between aerodynamics and structural response from aerothermal loading, ablation/pyrolysis, localized heating, and surface-to-surface radiation. To validate the FSMI software toolset's applicability to the high-speed environments of interest combined with a localized heating source, a series of test campaigns have been conducted to gather validation data of multiple high-temperature materials in high-enthalpy environments subject to localized radiative heating. The goal of the current work is to extend the range of applicability and provide the best-informed modeling of the comprehensive physics by exploring ablation-dominated high-altitude reentry conditions. This presentation will focus on the test campaign conducted at the IHF in combination with the Laser Enhanced Arc-Jet Facility (LEAF) to provide localized radiative heating supplied by a high-energy laser (HEL) to augment the aerothermal environment. Test data includes measurements of the arc-jet conditions, videography, thermography, in situ recession measurements, pre- and posttest profilometry scans of the test articles, in situ recession measurements, hyperspectral data, emission spectroscopy, mass loss measurements, in-depth temperature measurements, and characterization of the HEL beam profile. Good agreement was obtained between the test data and the FSMI results. In general, the FSMI simulations overpredict the temperature at the center of the beam profile by 10 to 15% but the predictions are bounded by the measured temperature at the edge of the beam profile. Predicted recession was also compared to posttest profilometry measurements with differences being as little as 3% for some cases.

The role of oxygen (absence) on the spallation of charring ablators

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Abstract

We discuss recent findings from inductively coupled plasma wind tunnel experiments on the spallation of lightweight charring ablators. Spallation effects due to flow shear stresses and internal pressure build-up have been the subject of renewed interest by the ablation community [1, 2, 3]. A direct comparison of PICA and FiberForm ablation under supersonic air and nitrogen plasma revealed distinct processes attributed to the presence of oxidation reactions, or absence thereof. Spallation in nitrogen plasma is characterized by intermittent particle release events, attributed to carbonaceous deposits that accumulate at the ablator surface. These precipitates originate from carbon sublimation and nitridation products that subsequently redeposit on the layered ablator surface, decreasing surface permeability. Particle release events occur as a result of the consequent increase in interior pressure caused by continued sublimation and production of pyrolysis gases beneath the carbonaceous deposition. These effects result in dominant contributions to the overall ablation processes, where unsteady spallation can account for upwards of 45% of the total mass loss in nitrogen plasma, with immediate implications to heat shield design. By contrast, no comparable carbon depositions or unsteady particle release is observed in air plasma at similar enthalpies, suggesting that, while sublimation and nitridation processes are active, all gaseous carbon is consumed by atomic oxygen near the surface. Overall our results provide new insights on the high-temperature ablation regime, where the tight interactions of sublimation, carbon deposition, and boundary layer carbon/oxygen reactions require further investigation.

Keywords: Spallation, Ablation, Thermal Protection Systems, Erosion, Oxidation

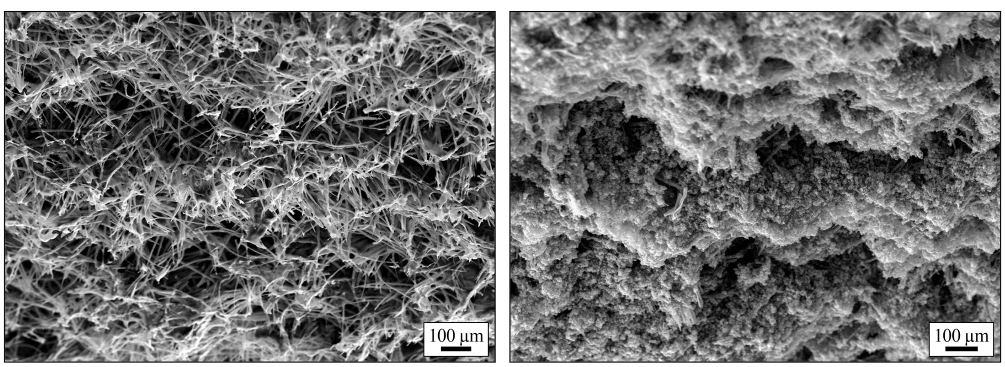

Figure 1: Microstructure of low-density ablator exposed to supersonic air (left) and nitrogen (right) plasma. Notable carbon deposition is observed for the nitrogen case, where particle accumulated at the layered ablator structure and occlude surface porosity. This starkly differs from the oxygen-rich case, which is instead characterized by the classical fiber thinning of high temperature oxydation.

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EXOMARS ROSALIN FRANKLIN MISSION: HEATSHIELD DEVELOPMENT AND TESTING ACTIVITIES

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Abstract

Over the past 25 years, the exploration of Mars has driven the development of cutting-edge European heat-shield technologies to ensure the safe entry, descent, and landing of robotic missions.

Originally, Russia was selected to provide the Proton rocket that would have brought the rover to Mars, as well as the Kazachok landing platform that would have served as the rover's platform on the Martian surface. Then, Russia invaded Ukraine, and within months, everything changed. ESA formally terminated the mission's cooperation with Roscosmos in July 2022.

As a result, ESA had to cancel the rover's launch, which had been scheduled for the fall, and rethink its options. NASA, which was originally part of the ExoMars mission but pulled out in 2012, may now step in again to help the mission move forward. The mission is now set to launch between September 21rst and December 26th in 2028, allowing for a landing around October 28, 2030 during northern hemisphere spring.

This paper provides an overview of the thermal protection system technologies development and testing for the latest European Mars missions namely Rosalind Franklin capsules ([1]). The future largest capsule heat-shields ever done in Europe (featuring a 3.8 m diameter, (Fig. 1)) is designed, manufactured, and tested by ArianeGroup SAS, showcasing Europe's expertise in thermal protection systems for planetary exploration. Build upon the post flight analysis of Schiaparelli ([2]), the thermo-ablative model of the Norcoat© Liège (a phenolic resin impregnated cork matrix) has been enriched through new several plasma test campaigns (Fig. 2), which included different tile /step /gap patterns as well as artificial micro-meteoroid induced damage. Coupled analysis between thermal response including pyrolysis and multi ablation modes (chemical, mechanical, and atmospheric dust induced) ablation has been implemented in the standard material model and is now the new reference for the heat-shield sizing. The front-shield aerothermal instrumentation package has been also qualified during this plasma torch campaign. As it is crucial for the future capsule sizing and safe optimization, a large effort has been devoted to embed a comprehensive set of thermal plugs, pressure and resistive ablation sensor. The Norcoat© 4011 radio-transparent thermal protection is also selected to equipped the back shell antenna patches (Fig. 3) . Norcoat© Liège dedicated linking tiles surround the antenna patches, which was also part of this qualification campaign.

The heat-seal flexible coupling interface between front and back shield was tested under representative high enthalpy convective fluxes and confirm the robustness of the material choice and assembly design. If that first development campaign have been done in air plasma, the final qualification one will be performed under CO2 environment to gain in representativity.

The RFM mission heat-shield development is funded under TASI contract No. 1550008461.

Keywords: In-depth heating, cork ablator, Thermal Protection System, ablation, Norcoat© Liège, Simoun

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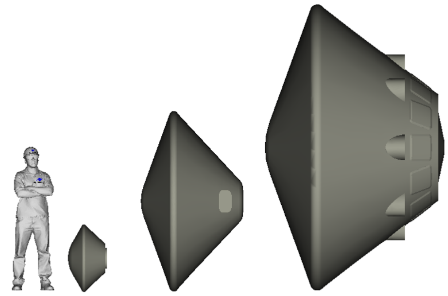

Figure 1: Beagle2 (left), Schiaparelli (middle) and Rosalind Franklin (right) capsule, showing the growing European ambitions over the years

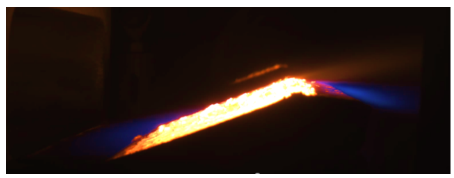

Figure 2: SIMOUN (arc-jet heater) wedge specimen for the tile pattern and aerothermal instrumentation qualification campaign

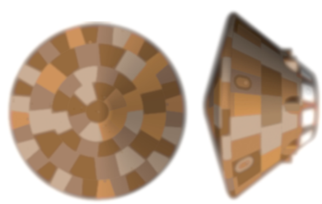

Figure 3: RFM capsule preliminary TPS pattern at Critical Design Review phase

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Acusil IV Model Development

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Abstract

Acusil IV is a silica fiber and silica-microballoon-filled silicone resin and is produced by Peraton Corporation. Acusil has been used for decades on both high-speed vehicles and NASA return capsules including being used on the Mars 2020 entry vehicle.

The original TPS model was created by ITT (the material manufacturer at that time) under the composites and advanced materials (CAM) program in February 2008, funded by the US Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC). It was intended to capture the thermal ablation and pyrolysis behavior of Acusil IV in a Charring Material Thermal Response and Ablation (CMA) thermal model, with the goal of using that model to predict material behavior in missile flight environments.

RTX TPS IRAD test data points were completed at much higher heat flux levels and show material survivability at conditions significantly above the original test measurements. The results of these tests were that the material did have the capability to survive but that the model, in its current form, showed complete material failure. Some of the test results will be highlighted along with an overview of the method used to extend the current modeling approach to the silica melting point.

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Preprint submitted to Proceedings of the 15th Ablation Workshop *October 23, 2025*

C/SiC Oxidation Limit

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Abstract

Silicon Carbide (SiC)-based composites are of interest for 'hot' structure hypersonic vehicle designs because they can maintain shape stability to temperatures between 1500-2000°C depending on oxygen partial pressure. Under these high temperature conditions, when exposed to oxygen (as during hypersonic flight) silicon carbide will form:

- A protective condensed-phase oxide (SiO2) in what is known as passive oxidation.
- A volatile sub-oxide (SiO(g)) in what is known as active oxidation.
- Or a transitional state between these two modes of oxidation where both mechanisms are present with varying reaction rates occurring between these states.

Silicon Dioxide (SiO2), also known as silica, is commonly found in nature as quartz and is a glass/ceramic that protects the substrate from exposure to further oxidation. Silicon Monoxide (SiO(g)) is a gas and will rapidly leave the surface under flight environments. The amount of the condensed-phase oxide (SiO2) versus volatile sub-oxide (SiO(g)) formed is therefore dependent not only of the conditions present such as temperature and pressure but also on the amounts of materials available for these reactions to take place.

A literature search of data was completed to establish a thermal limit for SiC materials. Some results from recent arc jet tests used to validate and enhance our understanding of this materials behavior under these high temperature conditions will be presented.

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Modeling and measurement of carbon-carbon ablation in the Sandia Hypersonic Shock Tunnel at various enthalpies and surface temperatures

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Abstract

Results from carbon ablation experiments performed in the Hypersonic Shock Tunnel (HST) at Sandia National Laboratories are presented. These experiments build on previously published data on graphite ablation in the HST by exploring the effect of parameters such as surface temperature, flow enthalpy, and surface roughness on the ablation of carbon-based materials. Two different surface temperatures were investigated – about 1900 and 2150 Kelvin, respectively – and the concentration of carbon monoxide downstream of the ablating samples was measured to monitor the ablation rate. Similarly, we conducted experiments under two different flow enthalpy conditions: the first with about 3.8 MJ/kg, and the second with about 10.2 MJ/kg. We observed that the concentration of carbon monoxide increased by about a factor of two for the higher enthalpy condition suggesting a higher ablation rate, which is likely due to the higher dissociation fraction of oxygen in the flow. These experiments were repeated on fiber-reinforced carbon-carbon (C/C) composite samples to investigate the effects of the carbon structure and morphology on its ablation. A slightly higher concentration of carbon monoxide was detected in the C/C experiments than the graphite ones, which suggests faster ablation of the composite material than graphite.

Finally, numerical simulations of the experiments were performed using both equilibrium and finite-rate surface chemistry models to assess the performance of current chemistry models to predict the material ablation. The finite-rate air-carbon ablation (ACA) model outperformed equilibrium chemistry and showed good agreement with the experimental data.

Keywords: Carbon ablation, gas-surface interaction, finite-rate modeling

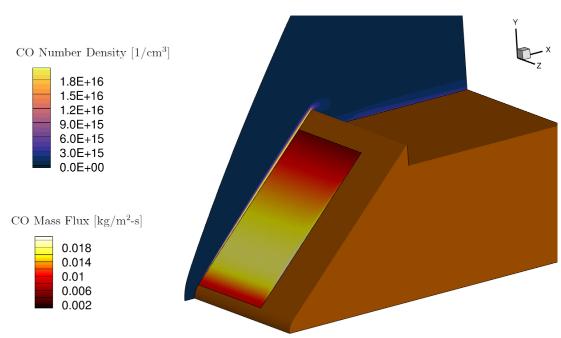

Figure 1: Simulation of carbon ablation in the HST showing CO number density and surface mass blowing rate.

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Towards Realistic Surface Ablation Modeling of 3D Orthogonal Architectures

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Abstract

Direct Simulation Monte Carlo coupled with the marching cubes algorithm is a proven computational method to model ablation of objects subjected to hypersonic flow conditions [1]. However, this implementation is known to result in numerical instabilities that generate artificial surface roughness. Recent work by Hong et al. [2] showed that a newly developed algorithm where the implicit surfaces are defined with multi-point and multi-values results in a more accurate surface regression. In this paper, we use the newly developed algorithm to analyze the influence of these numerical artifacts on the ablation of a 3d orthogonal synthetic mesh (shown in Fig. 1). Given the difficulty of obtaining well defined experimental data, synthetic (i.e., digital twin) surface meshes were generated using the PyVista package [3], allowing for a flexible approach to control tow architecture and enabling a clearer analysis of the ablation phenomena.

Keywords: 3D orthogonal weave, DSMC, hypersonic flow, marching cubes, digital twin

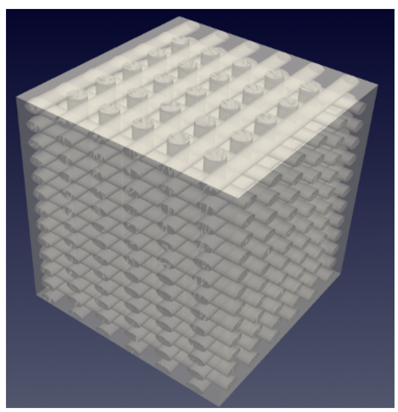

Figure 1: Representative synthetic surface mesh generated with PyVista .

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Conservative numerical modeling of an ablative charring heat shield under deformations

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Abstract

During atmospheric hypersonic re-entry, the heat distribution within the thermal protection system (TPS) is dampened by the in-depth chemical degradation of materials - called pyrolysis -, and by a surface physico-chemical degradation - called ablation. The aim of this work is to enhance pyrolysis modeling by considering solid deformations in order to describe more accurately the solid geometry variations resulting from swelling and ablation. The further aim of this study is to ensure mass and energy conservation during the pyrolysis-thermal coupling of heat shield under deformations. First, an overview of macroscopic modeling of pyrolysis is done. Arrhenius laws are employed for the density variation prediction. Then, thermal expansion, swelling and shrinkage are investigated as a consequence of material degradation, in addition to ablation. This analysis explores a pyrolysis-thermal model preserving mass and energy conservation during deformation and a number of numerical resolution maintaining numerical conservation. Finally, the model and methods are validated on ablation [1] and swelling [2] test cases from the literature and then applied to in-house experimental cases. The simulation results are in reasonable agreement with reference data and experimental data. Including swelling provides a closer approximation of wall evolution during hypersonic re-entry simulation.

Keywords: Pyrolysis modeling, solid deformations, conservation laws, Numerical resolution

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Enabling Rapid Flight Integration of Advanced Hypersonic Thermal Protection System (TPS) Materials: Grand Challenge Project Summary

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Abstract

An end-to-end workflow was developed to predict the performance of advanced thermal protection system materials (TPS) in hypersonic conditions. Over a three-year project span, three types of carbon/carbon composites of varying density and two types of ceramic matrix composites of varying processing method were investigated. Hundreds of samples were manufactured for material properties, ground, and flight testing. These data informed a three-way-coupled (aero-thermal-mechanical) full-order model (FOM) capable of simulating the TPS of a notional hypersonic vehicle over an entire trajectory. A robust method using experiment and mesoscale modeling was developed to predict material properties. The TPS thermal/ablative response was then predicted using a variety of engineering surface chemistry models ranging from basic equilibrium through modern finite-rate reaction sets. A unique credibility approach added ablation experiments in an inductively coupled plasma torch and a hypersonic shock tunnel to more standard data obtained in an arc-jet and laser-heated wind tunnel experiments. Also integral were extensive flight test thermal data obtained for every project material in 2025, with future recoverable samples expected in 2026. With this extensive dataset, a framework to propagate material property and ablation modeling uncertainties through an entire notional hypersonic trajectory was developed. The FOM was used to train and develop a coupled aero-thermal reduced order model (ROM) based on modal reduction via proper orthogonal decomposition. This novel ROM was 90% as accurate as the FOM but ran 25,000× faster.

Keywords: End-to-end, carbon ablation, finite-rate modeling, reduced order modeling, composites

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Characterization of PICA-NuSil Catalytic Recombination Efficiency in Air

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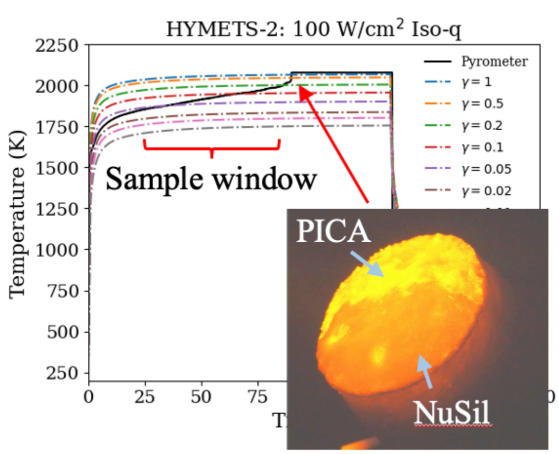
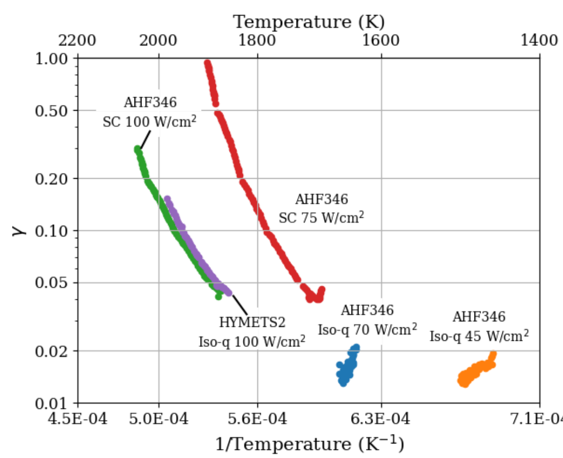
Abstract

Accurate predictions of the material response of ablative thermal protection systems (TPS) are critical for the design and sizing of heat shields on planetary entry spacecraft. Surface coatings, while a small component of the TPS architecture, have the potential to yield an outsized impact on the TPS thermal response by altering chemical recombination processes at the surface. In this work, the catalytic recombination efficiency γ of NuSil-coated PICA (referred to herein as *PICA-NuSil*) is characterized for air atmospheres using data from arc jet ground testing. The approach reconstructs the catalytic recombination efficiency of PICA-NuSil by comparing predictions of the material response behavior of test articles for varying values of γ with experimental surface temperature measurements. Using data from multiple arc jet ground test campaigns with a wide range of conditions, γ is reconstructed for surface temperatures ranging from 1450 K to 2025 K. For surface temperatures less than 1700 K, the catalytic recombination efficiency of PICA-NuSil in air is insensitive to variations in wall temperature, with values of γ in the range of 0.01 to 0.02. For surface temperatures above 1700 K, the catalytic recombination efficiency increases exponentially with an Arrhenius-type temperature dependence, up to a value of 0.2 at 2025 K. These results provide a baseline characterization of catalytic recombination efficiency for more robust predictions of TPS material response for Earth-entry spacecraft which leverage PICA-NuSil as a heat shield platform.





Surface pattern formation due to differential ablation

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Abstract

Surface patterns are known to form on ablating materials under both high-speed ground and flight test conditions when the flow is both turbulent and supersonic. Linear instability of the surface due to differential ablation has been proposed as a mechanism for the formation of crosshatching surface patterns due to their regular rhomboidal patterns. We present a local linear framework to study the stability of coupled fluid-ablation systems, with particular emphasis on the stability of the surface due to differential ablation. This system is represented schematically in Fig. 1. The linear stability of both laminar and turbulent compressible boundary layers over sublimating surfaces are studied. Under thermal equilibrium conditions, the laminar results agree with experimental observations of a stable surface, however the surface can be destabilized by increasing the wall temperature above the equilibrium adiabatic condition. A quasi-steady fluid model is introduced, where the forced response of steady wavy walls with sublimation is shown to accurately reproduce the full unsteady stability results. This quasi-steady model is then used to assess the ability of RANS turbulence models to accurately predict surface stability by comparison of the relevant wavy wall surface quantities (pressure, heat flux, and shear stress) with LES solutions. Finally, the existence of linear surface instabilities in turbulent boundary layers, and their correlation with crosshatching, is investigated.

Keywords: Surface patterns, ablating interfaces, crosshatching

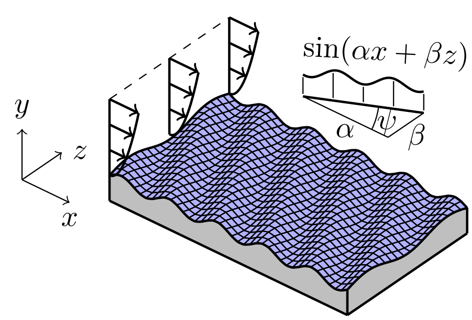

Figure 1: Schematic of local linear stability system.

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CARS temperature and species measurements in Illinois Plasmatron X

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Abstract

Laser diagnostics have revolutionized reacting flow research by providing unprecedented space and time resolution for multi-parameter measurements in hostile luminous flows. Coherent anti-Stokes Raman scattering (CARS) has an established track record of temperature and multi-species detection in facility scale combustion and plasma environments. We report several recent CARS measurements from the University of Illinois CHESS Center's Plasmatron X, where the method provides both reliable free-jet boundary conditions and spatial resolution of ablation boundary layers. Plasmatron X presents temperatures up to 5500 K at low static pressures from 55 to 200 mbar, placing coherent Raman signal photons at a premium. Thermometry in the free jet of both air and CO_2 plasmas is demonstrated, where temperature is inferred by fitting the Raman Q-branch spectra of the N_2 and CO ground states. We additionally discuss spatially resolved stagnation-region boundary layer profiles near carbon ablator surfaces and cold catalytic copper walls, previewed in the Figure below. Profiles of temperature and CO product mole fraction have been obtained simultaneously with surface recession and pyrometer temperatures for 8 graphite and 2 PICA ablation experiments, while significant thermal nonequilibrium is observed in the presence of the catalytic copper wall.

Keywords: Ground testing, inductively coupled plasma, laser diagnostics, temperature, species, CARS

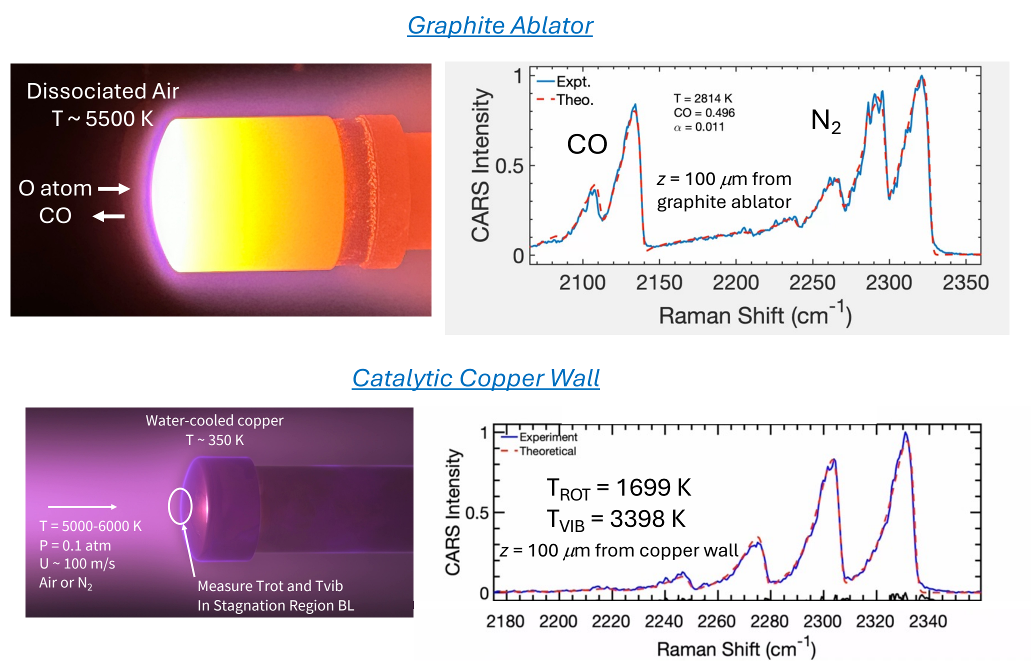

Figure 1: *CARS measurements in stagnation boundary layer flows established in Plasmatron X. (upper) Graphite ablator and CO/N_2 temperature/concentration measurement; (lower) catalytic copper surface exhibiting nonequilibrium rotational/vibrational temperatures in N_2*

Investigating optical transmissivity of windows coated by laser-ablated PICA

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Abstract

Due to high-temperature and low-pressure conditions during entry, pyrolysis and ablation products such as phenolic-impregnated carbon ablator (PICA) can be deposited on the radiometer windows, resulting in significantly reduced transmissivity. The reduction in transmissivity can lower the signal level reaching the radiometer sensing element. It is imperative to systematically investigate how the transmissivity is affected as pyrolysis and ablation products are deposited. We can investigate these effects by using our pulsed laser deposition (PLD) to deposit PICA onto glass and sapphire substrates, materials typically used as windows in sensors. This process is partially depicted in Figure 1, showing the instance in which a pulse evaporates some of the PICA target onto a substrate suspended above. Using our PLD vacuum chambers, we can control the pressure inside the chamber to be equivalent to that of the upper atmosphere to better simulate low-pressure conditions, as well as take In Situ ellipsometry data at discrete values ranging from 0.74 eV - 5.9 eV. This real-time data can be used to calculate the extinction coefficient (k) and index of refraction (n) at any time during the deposition process. After deposition, a spectrometer is used to acquire optical transmission data of the ablated products, at various conditions and times, on the different window-like materials. Measurement of the transmissivity of these substrates using spectrometers and ellipsometry can give insights into how radiometers may be affected by ablated products.

Keywords: Pulsed laser deposition, Spectrometer, Ellipsometry

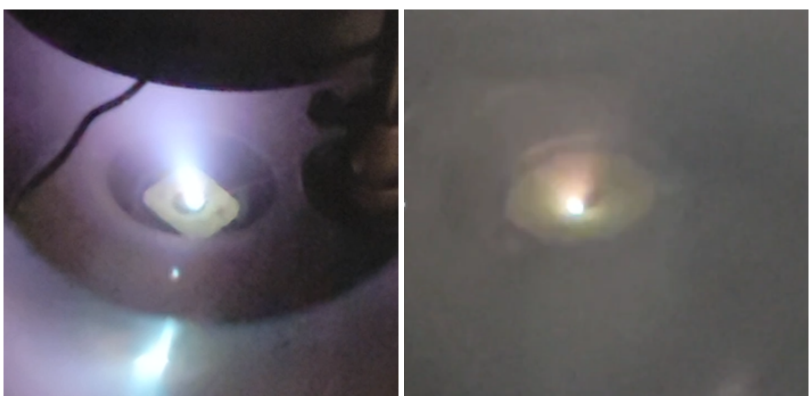

Figure 1: Depiction of PLD process in 12 mTorr(left) and vaccum(right)

Modeling Thermal Protection System (TPS) Ablation with the Unified Flow–Material Solver under High-Enthalpy Conditions

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Abstract

Enabling thermal protection system (TPS) design by analysis requires the development of high-fidelity tools that couple flow, chemistry, and material response. A major challenge is defining unified approaches that accurately capture the material interface while accounting for pyrolysis gas flow, heterogeneous reactions, and material degradation.

In this work, we extend the one-domain porous media approach [1, 2, 3, 4, 5] through the Unified Solver [6, 7, 8, 9] to study two representative thermal protection system (TPS) problems. The first application examines cavity defects, where the blowing of pyrolysis gases through the porous cavity walls produces a measurable reduction in surface heat flux. The second application focuses on FiberForm oxidation under high-enthalpy conditions representative of the UIUC PlasmatronX facility. Here, the Unified Solver captures the material interface progression driven by heterogeneous oxidation reactions. Due to the low Thiele number, we observe a stronger contribution of volume ablation relative to surface ablation, consistent with the internal consumption of carbon within the porous microstructure.

The Unified Solver's capacity to model strongly coupled thermochemical and flow processes in TPS materials under extreme entry conditions is demonstrated by these studies, which do not rely on ad hoc boundary conditions or remeshing of the computational domain.

Keywords: CFD, Material Response, TPS, Ablation

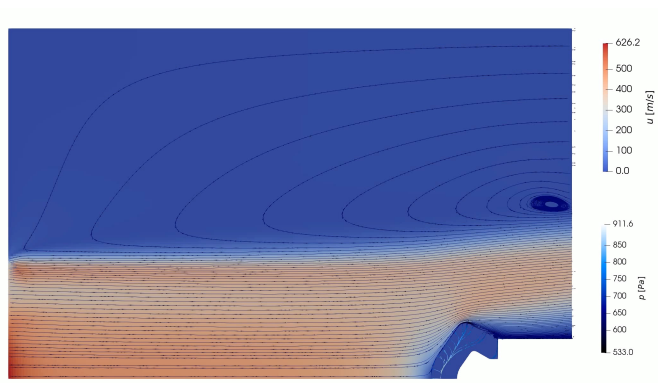

Figure 1: Simulation of FiberForm under representative conditions of the UIUC PlasmatronX facility using the Unified Flow-Material Solver.

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A Non-Equilibrium Boundary Layer Framework for Ablation Modeling

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Abstract

The study of thermal protection materials for atmospheric re-entry requires accurate modeling of gas–material interactions in the vicinity of the surface. The numerical solution of boundary-layer equations provides an effective strategy to investigate the compressible flow near the wall and finite-rate heterogeneous chemistry phenomena that arise at high temperatures. Compared to solving the full set of Navier–Stokes equations, the boundary layer formulation enables a more efficient evaluation of aerothermal loads and chemically reactive flows.

We present a new open-source framework developed in C++ that integrates a chemically reacting boundary-layer solver called Blast (Boundary Layer Analysis & Simulation Tool), the state-of-the-art Mutation++ library [1] for computing thermodynamic and transport of high-enthalpy gas mixtures, and a new library for gas–surface interactions named NEST (Non-Equilibrium Surface Thermochemistry). The framework relies on the hypotheses of steady, laminar flow under local thermal equilibrium and the thin boundary-layer approximation. A comprehensive literature review was carried out and several of the most widely used surface-reaction models have been implemented in Nest, including phenomenological ablation[2, 3], the γ-model for catalysis[4, 5, 6], finite-rate catalysis[7, 8], and finite-rate ablation[9]. The framework architecture is briefly described with particular emphasis on the role of Nest, and preliminary results are presented comparing the behavior of these models.

Overall this effort aims to release Blast-Nest open-source to the aerothermodynamics community as a tool for analyzing new gas–surface interaction models, and guide the design of the experiments on TPS materials conducted at high-enthalpy plasma wind tunnels. An outlook into the future development of this framework is also provided, most notable coupling with material-response solvers.

Keywords: Boundary Layer, Ablation, Catalysis, Gas–Surface Interactions, Thermal Protection Systems

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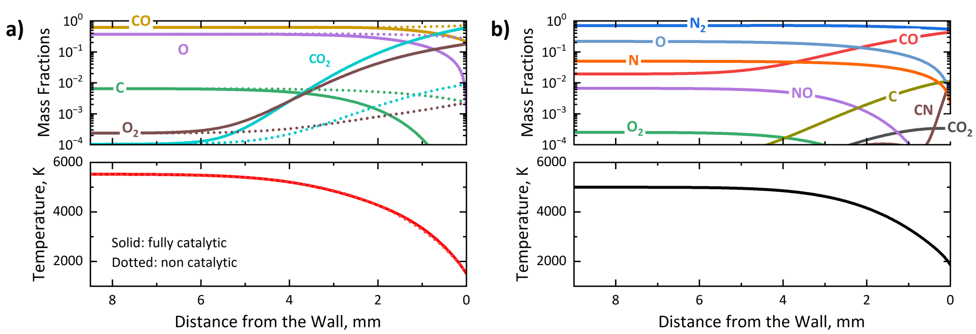

Figure 1: Examples Blast-Nest boundary layer solutions: a) CO2 with surface catalysis, b) air-carbon ablation

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Bayesian Learning of Air Carbon Ablation Model Parameters

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Abstract

Ablation modeling is a critical design aspect of Thermal Protection Systems (TPS) for high-speed vehicles. For flow over a carbon-based TPS in which the fluid contains gaseous oxygen and nitrogen, the Air Carbon Ablation (ACA) model was developed to simulate the finite-rate chemical reactions between the dissociated gas and the carbon surface, which can be used to determine the recession rate of the TPS. The ACA model is composed of 20 reaction mechanisms for oxygen, nitrogen, and carbon, which describe the interactions between the chemical species such as formation, desorption, and adsorption. The reaction mechanisms are driven by the relations between preexponential factors (PEFs), activation energies, and temperature. The ACA model can be utilized in a CFD code to simulate gas-surface interactions, as well as configured into a zero-dimensional reactor that can simulate the reaction products from molecular beam experiments.

The ACA model can theoretically calculate gas-surface reactions with high-fidelity, but it is limited by the high degree of uncertainty in the PEFs and activation energies, which cannot be directly measured. Thus, these model parameters were calculated such that the ACA model fits the reaction probability data generated by constant-flux molecular beam experiments. The reaction probabilities from the experimental data also carry a degree of uncertainty, which adds difficulty to the determination of the ACA model parameters. To address the uncertainty in these model parameters, we utilized Bayesian inference to extract their probability distributions. Using Bayesian inference allows us to define the uncertainty in the model in the form of a posterior probability distribution of the model parameters with respect to both the prior uncertainty in the model parameters and the uncertainty in the experimental data, which maximizes the utilization of all available data. To perform the Bayesian inference analysis, random samples of the PEFs and activation energies were generated and fed into the ACA model to calculate reaction probabilities with respect to temperature. Each ACA model output, generated by a random model parameter sample set, was evaluated against the molecular beam data to test the likelihood that it represented the true value. The random samples were fed into a Markov-Chain Monte-Carlo algorithm to iteratively develop the posterior distributions of the parameters.

The Bayesian inference results showed that the most-likely value of the PEFs could be determined as well as the uncertainty range, which could be propagated forward into the reaction probability curves. Bayesian inference proved to rigorously define the uncertainty of the ACA model, providing a more complete understanding of the physical characteristics of air-carbon ablation.

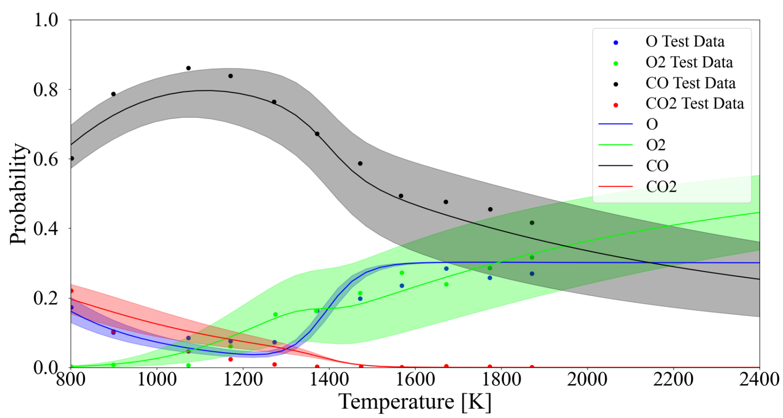

Figure 1: Prior predictive curves for the species reaction probabilities with their 95 percent confidence intervals

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Mapping ablative atmospheric entry onto the conditions of ground-test facilities

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Abstract

Thermal protections systems must withstand intense conditions during atmospheric entry. Supersonic plasma and arc-heated wind tunnels offer clear advantages for testing these materials, mimicking the intense heat-, mass-, and momentum-transfer of hypersonic boundary layers. Various subsonic and benchtop apparatuses remain useful for materials screening, model development, and code validation; however, the order-of-magnitude discrepancies in scale, velocity, and enthalpy obfuscates the selection of optimal test conditions.

This presentation will compare facility test conditions to various atmospheric entry cases. The objective is to reduce the complex aerothermal environment of flight into simple test conditions replicable in ground-test facilities, such as pressure, boundary-layer conductance, and heating rates. These ‘ablation maps’ are compared to operating envelopes of various established ground-test apparatuses [1, 2, 3]. Conditions are compared to ablation predictions of engineering-fidelity models [4], identifying where new information can be obtained, such as regimes for kinetically limited experiments. Ablative entry conditions will also be connected to correlations in the open literature, so the resulting test conditions can later be replicated and enacted.

Keywords: ablation, thermochemistry, finite rate, carbon, oxidation

Supported by the LDRD Program at Sandia National Laboratories. Sandia is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

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Pre-tabulated finite-rate ablation via Damköhler thermochemistry tables

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Abstract

Traditional ablation thermochemistry tables for atmospheric entry are derived from boundary-layer element diffusion assuming homogeneous and heterogeneous thermochemical equilibrium at the vehicle surface. Prior techniques for finite-rate surface reactions predominantly embed specific heterogeneous reaction models within the homogeneous equilibrium solution procedures and tables. We will present an alternative derivation that pretabulates thermochemistry solutions using the oxygen-consumption Damköhler number and a non-dimensionalized source of carbon ($B'_{C,s}$) [1]. This workflow enables alterations to kinetic rates downstream of thermochemistry calculations. Gas-phase equilibrium can be either enforced or suppressed via the carbon-to-oxygen ratio of the product gases ($\Delta_{C:O}$).

Figure 1 presents the thermochemistry table for ablation rate and predictions for a 1-cm stagnation-point radius. The model predicts kinetically limited ablation ($\overline{Da} \ll 1$) and diffusion-limited ablation ($\overline{Da} \gg 1$) partitioned into CO_2 and CO plateaus. The Damköhler thermochemistry tables are demonstrated on kinetics models from the literature and compared to the published results of similar techniques [2, 3, 4, 5, 6, 7]. A preliminary implementation into an engineering ablation code will also be presented.

Keywords: ablation, thermochemistry, finite rate, carbon, oxidation

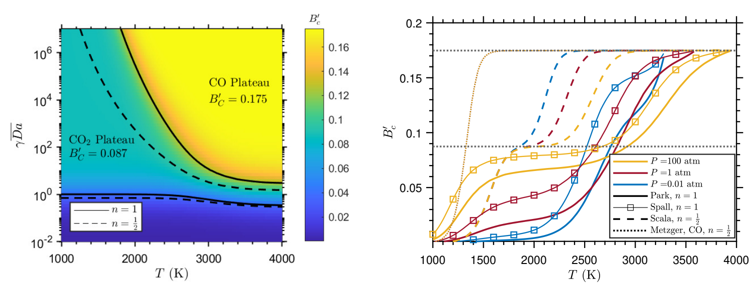

Figure 1: Damköhler thermochemistry tables alongside ablation rate predictions for a 1-cm stagnation point.

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Air-Carbon Ablation in Wave Rotor Environments

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Abstract awaiting government approval.

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Simultaneous measurements of N2, O2 and atomic O using rotational nanosecond CARS in an atmospheric-pressure inductively coupled plasma flow

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Abstract

Atomic oxygen is a key reactive species in numerous chemical processes spanning atmospheric reentry, combustion systems, and industrial plasma applications. In combustion environments, oxygen atoms serve as crucial intermediates controlling reaction pathways and flame characteristics while in the upper atmosphere they play essential roles in heat balance and ozone chemistry. During hypersonic atmospheric reentry at earth, atomic oxygen is the most agressive species leading to the oxidation and recession of heat shield materials. Currently common methods for atomic oxygen detection include two-photon absorption laser-induced fluorescence, cavity ringdown spectroscopy, and vacuum-ultra-violet absorption. Raman spectroscopy offers an attractive additional option for atomic oxygen detection, due to its ability to yield quantitative data and to provide simultaneous detection of multiple other molecular species with excellent spatial resolution. The electronic Raman transitions in atomic oxygen arise from the spin-orbit coupling within the ^{3}P ground state, producing measurable signals at 158.3 cm^{-1} ($^3P_2 \rightarrow ^3P_1$) and 227 cm^{-1} ($^3P_2 \rightarrow ^3P_0$). However, spontaneous Raman scattering from atomic oxygen has received limited attention and requires very long integration time for measurements with acceptable signal-to-noise ratio. Coherent anti-Stokes Raman scattering (CARS) increases the strength of the collected Raman signal by orders of magnitude. Detection of atomic oxygen with CARS has been demonstrated in hydrogen-oxygen flames using nanosecond lasers and in low-pressure oxygen-argon plasmas using hybrid femto-/picosecond lasers – reporting cross-sections and establishing the feasibility of the technique. In this work, we demonstrate first simultaneous rotational CARS measurements of N_2, O_2, and atomic-O at nominal temperatures ranging from 2500-6000K. The measurements are performed in the plume of an atmospheric pressure inductively coupled plasma torch fed with compressed dry air, 10 mm above the exit nozzle at different radial positions from the centerline. These results pave the way towards broadband multi-species measurements of species controlling the performance of thermal protection systems during hypersonic flight in oxidizing atmospheres with high physical and spatial accuracy.

Keywords: coherent anti-Stokes Raman scattering, high-enthalpy flows, atomic oxygen

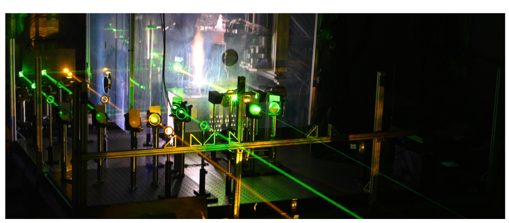

Figure 1: Photo of the utilized CARS setup.

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Thermal Conductivity Measurements in FRCI

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Abstract

The thermal properties of thermal protection system (TPS) materials vary during reentry due to the change in temperature, pressure, and gaseous composition changes. Modeling the thermal properties of TPS materials and how heat transfers through them as a function of these conditions is therefore important in determining the most efficient design for a given mission. Reusable thermal protection systems such as fibrous refractory composite insulation (FRCI) are used when moderate heat fluxes are expected. FRCI is a low-density TPS material composed of Nextel® and silica fibers that has previously been used on the Space Shuttle. The three primary modes of heat transfer in porous, fibrous materials such as FRCI that are present in this study are solid conduction, gaseous conduction, and radiation. Solid conduction occurs between the fiber-to-fiber contact within the fiber matrix and is a function of temperature and material geometry. Gaseous conduction takes place through the gases present in the pores of the TPS material. These gases conduct heat across the pores and can alter the heat transfer paths in the fiber matrix. The gaseous conduction in a fibrous TPS material is a function of temperature, pressure, fiber geometry, and participating gases. Finally, radiation is emitted, reflected, and absorbed by the individual fibers of the fiber matrix. The radiation heat transfer is dependent on several optical properties such as the extinction, scattering, and absorption coefficients of the TPS material. The effective thermal conductivity of the TPS material can be found as a superposition of these three primary modes of heat transfer. A testing apparatus utilizing the comparative cut-bar method has been developed that can measure the thermal conductivity of these fibrous insulation materials. This testing apparatus is located inside a thermal vacuum chamber that can be used to modify the sample environment to isolate the different modes of heat transfer. The heat transfer from gaseous conduction can be mitigated by bringing the sample environment to vacuum conditions. The contributions from radiation can be decreased by bringing the sample down to cryogenic temperatures. Due to the non-linear contributions from each mode of heat transfer, it is difficult to determine the heat transfer parameters using conventional linear methods. Genetic algorithms have been used to determine the contributions from each mode of heat transfer in FRCI by testing over a wide range of temperatures in vacuum and atmospheric pressure.

Keywords: Fibrous insulation, heat transfer, effective conductivity, genetic algorithm

Figure 1: Experimental set-up

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Oxidation transitions and interface bubbling in silicon carbide spacecraft TPS — An in-depth multiphysics modeling approach

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Abstract

Silicon carbide (SiC) is an important material for hypersonic thermal protection systems, yet it experiences complex thermo-chemo-mechanical degradation which remains difficult to model. Depending on how the external flow conditions affect the in-depth thermodynamic state, SiC may form a thermally-grown passive oxide layer, actively ablate, or form bubbles due to decomposition at the oxide/substrate interface. Here, we introduce a comprehensive multiphysics framework capable of simulating all three oxidation modes and their corresponding mechanical effects within one formulation. The model couples transient heat transfer, multispecies gas diffusion, and finite-deformation solid mechanics, while locally enforcing thermochemical equilibrium via embedded Gibbs free energy minimization calculations. Together, these components enable the natural prediction of oxidation transitions, including those that initiate from within the bulk. We apply the framework to β-SiC in neutral Ar/O_2 atmospheres and compare predictions against thermogravimetric measurements across oxidation regimes. The model reproduces experimental mass loss or gain trends and captures key relationships like the influence of mechanical loading on oxide growth. Our approach also simulates active-to-passive transitions in accordance with traditional Wagner-style models. Furthermore, for the first time, it also predicts the onset of interfacial bubbling, which we show is associated with a large pore-gas overpressure deep within the material. In turn, this overpressure may rupture the silica scale, precipitating a transition to active ablation.

Keywords: Silicon carbide, embedded chemistry, multiphysics, oxidation, ablation, bubbling, poromechanics

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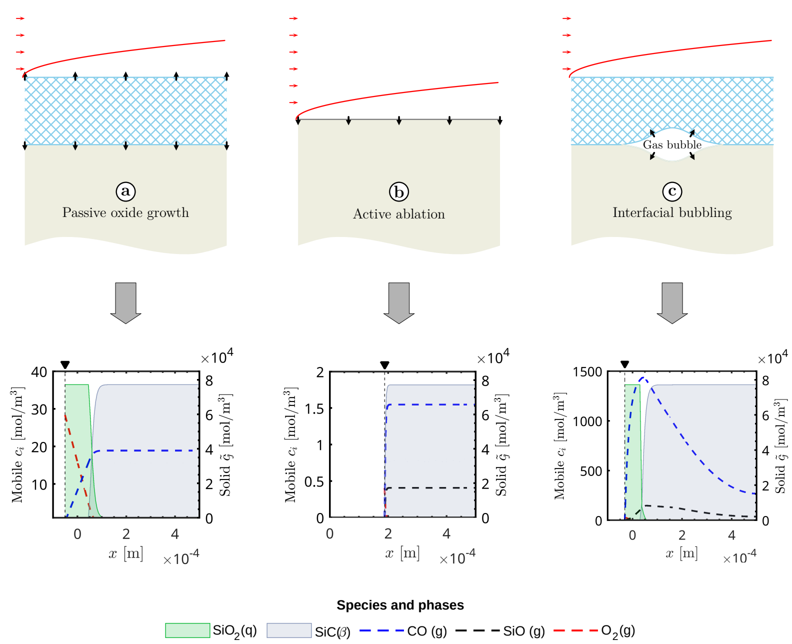

Figure 1: In-depth multiphysics simulations reveal three distinct oxidation modes, which arise under different environmental conditions.

2

Surface Analysis of High-Temperature Graphite under N_2/Ar Plasma

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Abstract

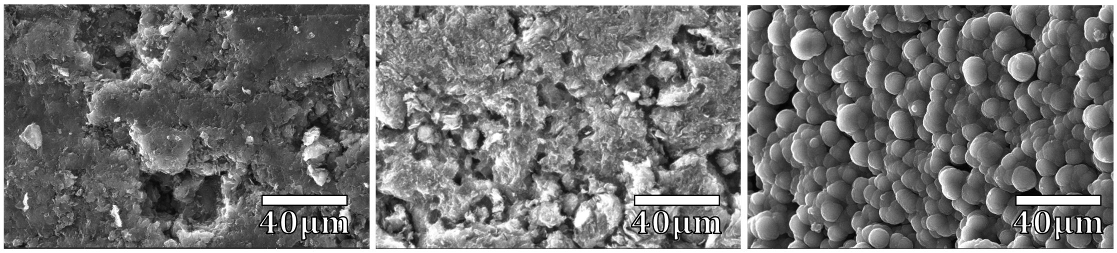
The complex nature of heterogeneous chemistry in atmospheric re-entry has driven extensive Thermal Protection System (TPS) research [1, 2, 3]. Plasma composition dictates material response, making ground-based plasma testing critical for improving TPS performance. Oxygen-rich plasmas at high temperatures typically ablate carbon materials through fiber thinning or localized pitting [4, 5], whereas nitrogen plasmas are less reactive, and surface modifications from nitridation remain limited at moderate temperatures [6, 7, 8]. At temperatures beyond 2000 °C, where nitridation is active and sublimation becomes significant, more distinct features emerge. Han *et al.* [9] reported observations of carbon fibers in 3D carbon–carbon composites being transformed into graphitized globules at temperatures up to 3000 °C, suggesting a nucleation–growth mechanism. Similarly, Helber *et al.*[4] observed the formation of carbon nodules on fiber surfaces under oxygen-deficient plasma conditions at high temperature (2000-2600 K), consistent with a chemical vapor transport mechanism. More recently, Ringel [10] showed that deposit accumulation tracks proportionally with local temperature. These observations underscore the need for further studies of nitrogen plasma interactions with carbon materials to investigate the underlying mechanisms.

In this work, graphite was selected as a surrogate carbon material to investigate carbon nodule formation at ultra-high temperatures. Flow-reactor tests were carried out using a capacitively coupled plasma source, while maintaining stable surface temperatures through Joule heating of the sample. Graphite rods (Mersen Ellor+20, 1.5 mm diameter, 50 mm length) were tested in N_2/Ar plasma at temperatures of 1400–2500 °C and a pressure of 3.1 Torr. The plasma impinged perpendicularly along the sample length, with exposure times between 30 s and 300 s. Post-test characterization using SEM, XPS, and Raman spectroscopy was performed to assess how nitridation, sublimation, and re-deposition influence surface morphology, degradation, and chemical composition.

Figure 1 shows SEM micrographs of virgin sample and samples tested under N_2/Ar plasma at 1800 °C for 300 s and at 2500 °C for 90 s. The virgin sample exhibits a machined surface with fractured grains and inherent porosity. After exposure at 1800 °C only minor surface alterations are observed, with slight roughening and edge flaking. At 2500 °C, however, the surface morphology changes dramatically, dominated by densely packed globular nodules from submicron to several microns. The sample tested at 2500 °C fractured at the midpoint after ~90 s plasma exposure, and the resulting temperature gradient produced a morphological transition, with larger spherical nodules at the center that gradually decreased in size to smaller ones toward the edges. These nodules appear as coalesced semi-spherical particles, consistent with hierarchical growth. Raman spectroscopy shows a lower I_D/I_G ratio at the midpoint, indicating more graphitic order in larger globules, and a higher ratio at the edges, reflecting more disorder. XPS further reveals higher nitrogen concentration at the side region than at the midpoint.

Our results show that surface morphology depends strongly on surface temperature and exposure time. Below 2000 °C, the surface exhibits minor roughening with fractured grains, open porosity, and edge flaking, likely linked to nitridation. Above 2000 °C, globular structures begin to form, suggesting a shift toward surface restructuring. At higher temperatures and longer exposures, these features appear to coalesce into semi-spherical particles, indicating a possible hierarchical growth mechanism. These findings confirm that globular structures occur not only in carbon fiber but also in graphite, and are closely linked to carbon sublimation and re-deposition. Future work will characterize these features under varied plasma conditions to correlate their formation with composition and growth kinetics.

Keywords: Carbon Nitridation, Carbon Redeposition, Capacitively Coupled Plasma, Surface Characterization



(a) Virgin (b) 1800 °C (c) 2500 °C

Figure 1: SEM micrographs of (a) virgin graphite, (b) graphite tested at 1800 °C for 300 s, and (c) graphite tested under Ar/N plasma at 2500 °C for 90 s

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Summary of Oxford Experiments on Heat and Shear Stress Augmentation due to Roughness and Blowing with Hypersonic Boundary Layer Edge Conditions

Matthew McGilvray, Wesley Condren, Chris Hambidge, Peter Forsyth and David Steuer

It is typical of many types of ablative materials to exhibit roughness and pyrolysis gas blowing as they decompose. Although engineering correlations exist for the effect of small-scale roughness on heat transfer and shear stress, the complexity of flow physics for elements whose height exceeds the sonic line of hypersonic boundary layers is largely unknown. Even less knowledge exists in the open literature on the coupled effects of multi-scale roughness and coupling to blowing.

Over the past five years, Oxford has undertaken a series of flat plate experiments in its High Density Tunnel at Mach 5. A series of different roughness patterns have been explored from revisiting the original low speed wire mesh and hemisphere experiments of Nikuradse, sinusoidal patterns representative of 3D woven fibre ablators and sawtooth patterns. This has included the variation of boundary layer edge Reynolds number, varying the roughness Reynolds number and roughness to boundary layer edge Reynolds numbers. Blowing is also assessed using a variety of inert gas mixtures with varying molecular weights and blowing parameters. Measurements of heat flux augmentation have been undertaken spatially using IR thermography and averaged over a larger area using cast silver calorimeters. A floating balance with sufficient response was developed to measure shear drag augmentation. Local pressure and concentrations have been measured with Pressure Sensitive Paint.

These results are compared to existing correlations and effects of roughness and blowing superposition are assessed.

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Design and Characterization of a Spinning Disk Flow Reactor for Graphite Oxidation Kinetics

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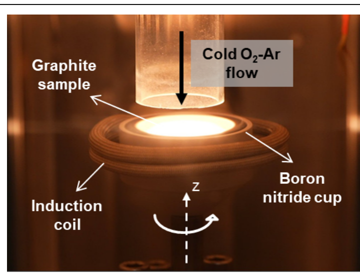
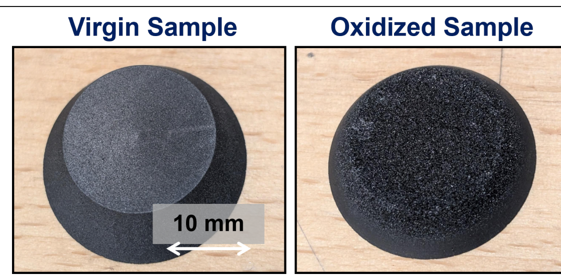
Abstract

High-temperature graphite oxidation is strongly influenced by the competition between intrinsic surface reaction kinetics and external oxygen mass transfer to the surface, particularly at higher pressures and temperatures. Under these conditions, the rate of chemical reactions at the surface can exceed the rate at which oxygen is delivered, resulting in a diffusion-limited regime where the measured rates no longer accurately represent the true oxidation kinetics. To address this challenge, a Spinning Disk Flow Reactor (SDFR) was developed based on the Von Kármán swirling flow principle to enhance convective oxygen transport to the reacting surface and alleviate mass transfer limitations. This technique has previously been employed to measure the reaction rates of oxygen with the basal and prism faces of pyrolytic graphite at 1100–2000 K, using 0.05–0.1% oxygen in helium or argon at atmospheric pressure [1]. Spinning disk experiments complement results from other flow reactor configurations without convective mass transport enhancements such as a cylinder in cross flow [2]. In the present work, graphite oxidation experiments were carried out with O_2 mass fraction of 0.45 in an Ar mixture at 1073–1673 K, under a chamber pressure of 2 kPa, and spin rates ranging from 0 to 6000 rpm. Graphite reaction rates were determined from measurements of carbon mass loss and were observed to increase with sample rotation speed up to 2000 rpm before reaching a plateau.

Keywords: Graphite oxidation, Spinning disk, diffusion-limited regime



(a) Graphite sample placed in a boron nitride cup in the SDFR.



(b) Virgin graphite sample and oxidized graphite sample at 1473 K for 300s.

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A Multi-Component Carbon Ablation Model from Molecular Beam Data

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Abstract

The Air-Carbon Ablation (ACA) model was developed by Prata et al. [1] as a high-fidelity, finite-rate model of carbon ablation, but was based only on vitreous carbon (VC) experimental data. Modern carbon ablative materials are more complex, requiring models that are valid for multi-component carbonaceous materials. For example, while the matrix and fibers in Carbon/Carbon (C/C) are both carbonaceous, they have different reactivities that cannot be simultaneously described by ACA. Modern carbon ablation models [1, 2, 3] cannot be used to describe arbitrary forms of carbon when the difference between materials is attributed to physical parameters such as the total number of active surface sites, since these models did not consider the proper treatment of such parameters. Recent molecular beam experiments on VC and Mersen graphite (MG) [4] allow for the development of a new finite-rate model that has similar trends to ACA across ranges of temperature and pressure but is also now valid for arbitrary forms of carbon. Physically based collision frequency arguments are used to develop new reaction rate forms that are fit to the VC and MG molecular beam data. This model will then be compared to new and historic molecular beam data across a range of materials.

Keywords: carbon ablation model, finite-rate, multi-component, surface sites, molecular beam

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Modeling of Graphite Material Damage Under Hypersonic Flight Conditions

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Abstract

Hypersonic vehicles operating in particle-laden flow experience surface degradation from mechanical erosion. In order to accurately design thermal protection systems and determine the vehicle's lifespan, the ability to predict erosion due to particle impacts is essential. New experimental data from both multiple and single-particle erosion experiments on graphite surfaces have been performed [1, 2]. These two independent data sets were used to develop a new empirical damage model that relates the volume removed to the total particle kinetic energy.

Flowfields were computed using the US3D CFD solver, for a 0.1m radius sphere-cone geometry at Mach 5 at 30km altitude (Figure 1). Particles sampled from atmospheric and volcanic size distributions were tracked using a Lagrangian approach. Local impact damage and erosion rates based on the new damage relation were computed.

Results show that erosion is dominated by particles that have high enough concentrations and sufficient kinetic energy. For this geometry, particles that trend towards the ballistic limit (≥ 5um) produce the highest damage and recession rates near the stagnation region. Typical stratospheric aerosols produce negligible erosion (10^{-6} mm/s), while the more extreme volcanic particle distribution can increase surface recession to millimeter-per-second rates.

Keywords: Particle-laden flow, mechanical erosion, erosion modeling

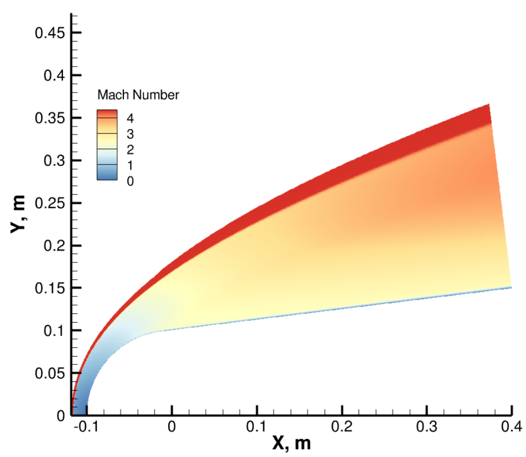

Figure 1: Two-Dimensional, axi-symmetric grid flowfield solution. Contours indicate Mach number.

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Anisotropy and hysteresis of PICA under compression

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Abstract

Efforts have been made to characterize the mechanical properties of the ablative thermal protection system material, PICA (Phenolic Impregnated Carbon Ablator) [1, 2]. Such studies have been instrumental in understanding failure in PICA, providing a valuable basis for the implementation of mechanical properties in ongoing modeling efforts [3, 4]. Further characterization of the mechanical properties can improve such models, providing more accurate results to help ensure material reliability. Our objective is to support this effort by testing PICA under a variety of compressive loading scenarios. Using a strain visualization method called digital image correlation (DIC), we can view strain on the sample surface as it undergoes loading (Fig.1a). Factors considered include sample orientation, cyclic loading, and different types of PICA. PICA is generally assumed to have planar isotropy, but our work indicates a difference in stiffness and maximum stress depending on the orientation in-plane, which can be seen in Fig.1b. This is supported by fiber orientation data, which shows a directional preference within the plane of assumed isotropy. Under cyclic loading in the through-thickness direction, PICA exhibits significant hysteresis behavior. After an initial loading-unloading cycle, the stress-strain curve for subsequent reloading shows significant softening. Once the maximum strain of previous cycles is surpassed, the stress-strain curve continues along the path expected of simple compression as seen in Fig.1a. This behavior is consistent with the Mullins effect, which is commonly associated with filled rubber [5], but has also been observed in other systems such as entangled metallic wire materials [6]. We have also observed a significant difference in maximum stress between heritage PICA and PICA-D under compressive loading in the through-thickness direction.

Keywords: PICA, compression, digital image correlation, mechanical properties

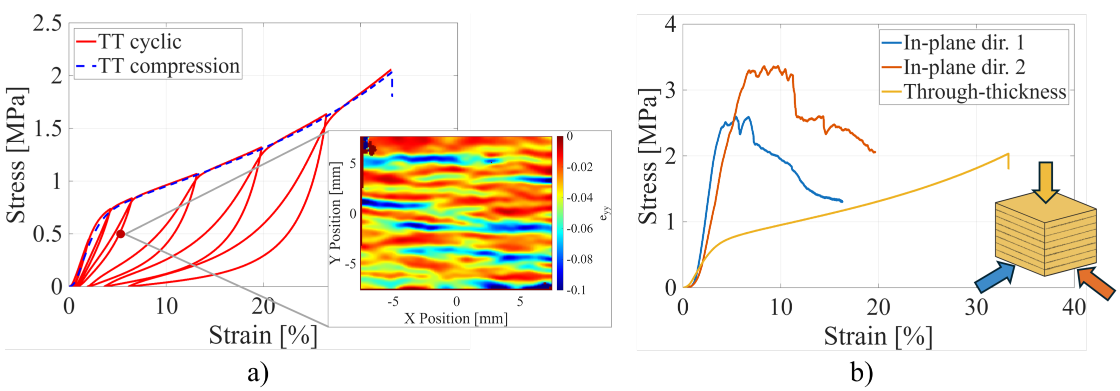

Figure 1: Stress-strain curves for PICA-D under compressive loading. a) Cyclic and simple TT compression with DIC strain field inset. b) Simple compression in the three primary directions.

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miniSTARscan: A Portable 3D Photogrammetry Rig for Arcjet Sample Scanning

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Abstract

Pre- and post-test scanning of samples exposed to arcjet and other high-enthalpy facilities is essential for quantifying material ablation, surface recession, and roughness evolution. Conventional high-fidelity 3D scanning solutions—such as handheld laser scanners or large photogrammetry rigs—are costly, require the use of proprietary software, and are not tailored for high-throughput standardized scanning.

The *miniSTARscan* system is an compact, automated, and portable photogrammetry-based scanner designed to achieve sub-millimeter accuracy. The rig combines three compact cameras with lightweight 3D-printed components, an aluminum frame, and modular LED lighting, enabling high-throughput scanning (sub-minute scans) at test facilities with tailored data pipelines. A dedicated graphical user interface automates calibration, image acquisition, 3D reconstruction, 3D mesh texture (e.g., colored mesh), alignment of pre- and post-test geometries, and several standard measurements (recession map, profile extraction, radius of curvature, surface roughness).

miniSTARscan will be released with an open-source hardware and software, providing a low-cost, highly-customizable alternative to commercial scanners. Its companion software is simple to use, integrates with common photogrammetry libraries, and interfaces directly with the in-house database (ArcBEAST) for streamlined data management and further analysis.

This combination of built-in analysis tools, affordability, and high-throughput enables repeatable high-quality scanning, standardizes detailed surface analysis, and eliminates scanning bottlenecks in facility operations.

Keywords: Recession tracking, photogrammetry, arc-jet, plasmatron, 3D reconstruction, portable scanning

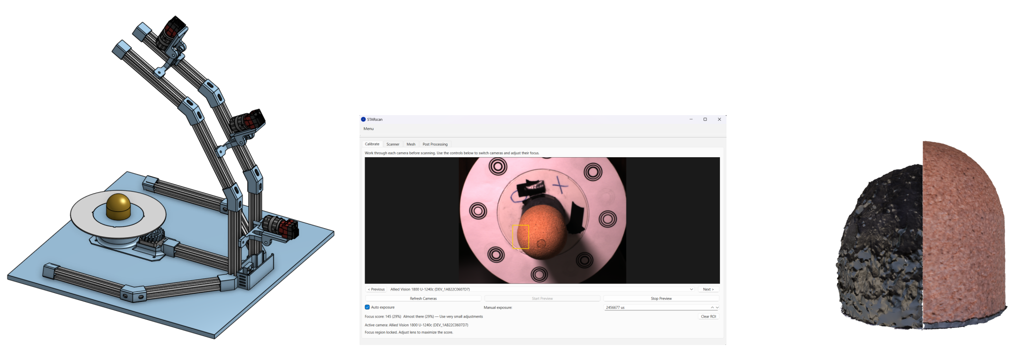

Figure 1: (Left) miniSTARscan portable rig; (center) graphical user interface; (right) miniSTARscan results for a cork sample tested in the plasmatron of the Von Kármán Institute for Fluid Dynamics

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Building Sustainable Data Infrastructure for NASA Thermal Protection Research: The BEAST Initiative

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Abstract

NASA's current data infrastructure for thermal protection system (TPS) research remains fragmented and project-specific. Arcjet test results are often stored as spreadsheets summarizing individual campaigns, with raw data scattered across local drives or cloud folders. Once projects conclude, these datasets are difficult to locate or reuse, and the absence of standardized metadata, version control, and provenance tracking limits cross-campaign analysis and long-term reproducibility.

To address these limitations, we developed the **BEAST** (Backend for Experiment Analysis, Storage, and Traceability) platform, a centralized database that ingests, structures, and visualizes arcjet data. BEAST provides queryable access to time-series and metadata records, enabling statistical analysis, material property tracking, and reproducible cross-test comparison. The system embeds version control, facility-configuration tracking, and material-sample lineage within a unified, searchable framework, establishing a sustainable foundation for data-driven TPS development. Beyond archival functions, BEAST streamlines facility operations through automated report generation, component-usage tracking, and interactive dashboards for operators and analysts. A shared web interface further supports coordinated test planning between principal investigators and test engineers.

Under the same initiative, companion tools extend automation to data generation and analysis. **arcjetCV** applies computer vision and machine learning to high-speed video to extract real-time measurements of material recession and shock standoff, while **STARscan** provides rapid 3D surface reconstructions of test samples before and after exposure. All tools share BEAST's data schema and provenance model, enabling seamless integration of imagery, mesh, and metadata.

The BEAST ecosystem represents a critical step toward reproducible, data-rich, and efficient operations across NASA's arcjet facilities linking data management, automation, and analysis to enhance scientific fidelity and mission readiness.

Keywords: Recession tracking, photogrammetry, arc jet, 3D reconstruction, database

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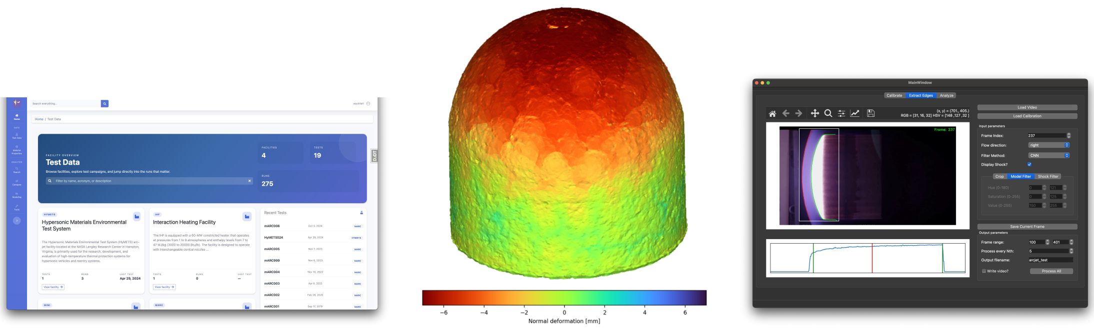

Figure 1: (Left) BEAST, (center) miniSTARscan normal deformation result, (right)arcjetCV.

Historical Particle Ablation Experiments Applied to Modern Environments

Kyle Gorkowski[a], Brody Hesseltine[a], Nicholas Pappafotis[a], Vincent Thomas[a]

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Abstract

During the 1970s, extensive particle impact experiments were conducted to characterize the ablation behavior of particles under high-velocity conditions. The data from these studies formed the foundation of what is now known as HEAT, also referred to as ATAC2, currently managed by CFD Research Corporation.

Today, particle environments are far better characterized than was possible at the time of the original studies. In this work, we show how the HEAT model responds to modern environments.

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Keywords: Particle Ablation, Environments

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Model Error Effects on Hypersonic Ground-to-Flight Extrapolation

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Abstract

Model development for hypersonic flows often relies on data from ground-based testing facilities. However, these facilities are typically unable to replicate all relevant physical phenomena and their associated timescales, leading to experimental data that may omit critical aspects of the flow physics. As a result, models calibrated against such data can exhibit significant errors. Inverse methods, which infer model parameters from data, are inherently sensitive to the quality and completeness of the input data. This raises concerns about the validity of applying these calibrated models to different conditions, especially in multi-scale problems where microscopic physics are upscaled for use in continuum approaches like Computational Fluid Dynamics (CFD). In such cases, the inferred macroscopic parameters may encapsulate multiple physical effects, reducing the generalizability of the model. Despite these limitations, calibrated closure models are often applied beyond their calibration regimes without rigorous assessment of their predictive capabilities. This issue remains underexplored in the context of hypersonic flow simulations and constitutes the central focus of the present work. The limitations of the calibrated models can be expressed mathematically through the concept of model error. State-of-the-art model error approaches consist on methods that either add a statistical correction term to the model prediction or embed the source of model error directly in a subset of model parameters of the given physical system. Estimating model error remains one of the most challenging open problems in uncertainty quantification and inverse analysis.

In this work, we investigate the impact of model error on hypersonic ground-to-flight extrapolation, with a focus on plasma wind tunnel experiments and ablation modeling. Our objective is to assess how uncertainties arising from both ablation and thermochemical models affect flight simulations, and whether the presence of these uncertainties could compromise the ability of ground-based tests to accurately reproduce flight conditions. By systematically propagating uncertainties for different parameter subsets, we aim to analyze their influence on key quantities of interest, including stagnation-point heat flux, temperature profiles, and species concentration distributions.

Keywords: Thermal Protection System, Ablation, Uncertainty Quantification, Bayesian Inference

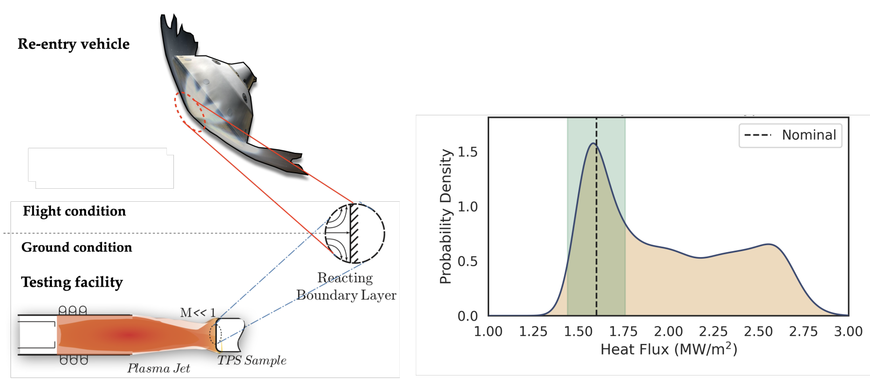

Figure 1: Ground-to-flight extrapolation sketch for a plasma wind tunnel experiment (left). Resulting stagnation-point heat flux probability distribution after model error propagation (right).

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Development of an Arc-Jet Preheating System within an Expansion Tube Facility for Hypervelocity Flow Testing of Ablating Test Models

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Abstract

Replicating atmospheric entry of hypersonic vehicles in ground-based test facilities requires accurate reproduction of both the flow-field and thermal boundary-layer conditions. Expansion tubes can generate test flows with flight-representative velocities; however, their transient quasi-steady test durations are insufficient for the model surface temperature to rise to levels required for studying ablation and coupled high-temperature effects. To address this limitation, the present work reports on the development of an integrated facility system, in which the OPG2 arc-jet plasma generator is installed within the test section of the Cold-driven Expansion Tube (CXT) at the University of Oxford. The high-enthalpy plasma flow generated by the arc-jet preheats the test model to elevated temperatures. Afterwards, the model is pneumatically actuated to align with the expansion tube just before the flow arrival. Fig. 1 shows the schematic of the facility. The new system aims to match key flow parameters, such as total enthalpy and heat flux, between the two facilities, enabling a comparative analysis of ablation phenomena under flight-representative conditions. Diagnostics include IR imaging, fibre-coupled spectroscopy, and high-speed imaging to characterise both the surface temperature and the flow-field. Details of the experimental setup, together with some preliminary results of heated test models exposed to hypervelocity flows, will be presented in the talk.

Keywords: Arc-jet, Expansion Tube, Ablation, Model Preheating

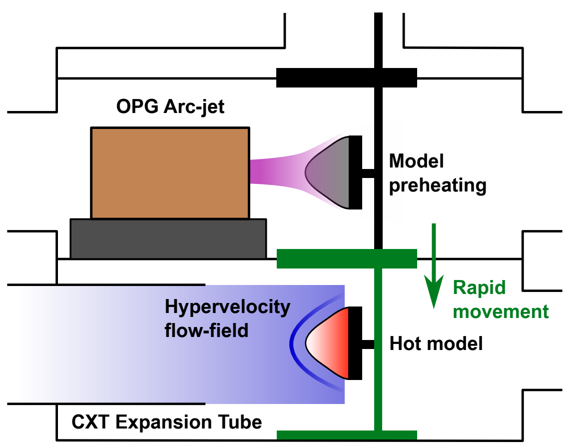

Figure 1: OPG Arc-jet Preheating in the CXT Expansion Tube.

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Engineering-Fidelity Damköhler Ablation Model Simulation Results

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Abstract

Recently developed carbon ablation models have become very accurate, but are still intractable for large-scale coupled simulations across trajectories. Simple engineering-fidelity ablation models solve this problem and have existed for decades [1, 2, 3], but are based off a limited set of experiments and are thus not as accurate or generalizable as needed. To address this gap, a new engineering-fidelity ablation model is created that directly uses the high-fidelity carbon ablation models instead of experimental data to generate pre-tabulated tables. The framework of this new model will be briefly described. A coupled simulation of the blunted-wedge shown in fig. 1 will be presented, comparing the new model to existing engineering-fidelity ablation models. The new model, using both ACA[4] and Park[5] rates, predicts similar trends to existing models but has generally lower predicted ablation at temperatures below the sublimation regime.

Keywords: Carbon, ablation model, engineering-fidelity, Damköhler number, blunted wedge simulation

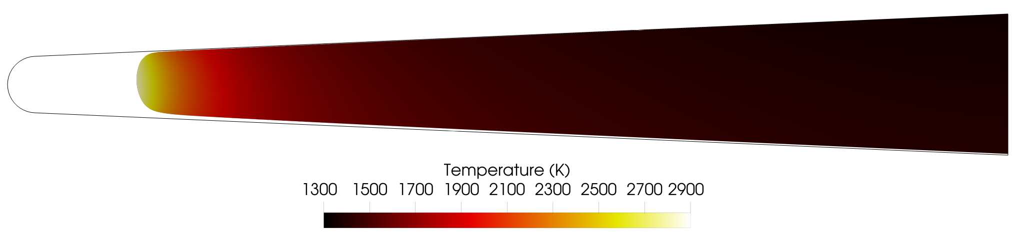

Figure 1: Temperature and recession of a simulated blunted wedge after 1000 s of exposure with the initial outline of the wedge. This simulation was performed using the Damköhler engineering-fidelity model with ACA.

Supported by the LDRD Program at Sandia National Laboratories. Sandia is managed and operated by NTESS under DOE NNSA contract DE-NA0003525.

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Finite-Rate Oxidation Modeling of Silicon Carbide in US3D

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Abstract

Ultra-high temperature ceramics (UHTCs) are often proposed for use on the leading edges and control surfaces of hypersonic vehicles due to their superior oxidation resistant properties. UHTC materials such as silicon carbide (SiC) may exhibit active or passive oxidation behavior depending on the gas state near the surface. Under passive conditions, a protective SiO_2 layer forms, limiting the diffusion of oxygen to the SiC substrate. If there is a transition from active-to-passive oxidation, a large decrease in the surface heat flux is observed due to the lower catalytic efficiency of SiO_2 relative to SiC. At high temperatures (>2000K), the oxide layer volatilizes and gaseous SiO is produced. Because the formation and volatilization of the oxide layer compete through multiple kinetic mechanisms, the transition from passive-to-active oxidation shows hysteresis (a formed SiO_2 layer can remain stable under active conditions). To quantify the behavior of both transition mechanisms under relevant hypersonic flight conditions, an existing finite-rate oxidation model for SiC [1] was recently coupled with the US3D computational fluid dynamics solver. The model solves a system of ODEs consisting of both catalytic and redox reactions to compute the species flux and SiO_2 layer thickness at each surface cell. Initial results compare boundary layer composition and surface heat flux profiles for the transition from active-to-passive and passive-to-active oxidation. The mass gain and removal of the SiO_2 layer is also compared over both cases.

Keywords: Silicon carbide oxidation, finite-rate modeling, oxide layers, hypersonic flow, CFD

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Modeling Swelling and Shrinkage with PATO's Pyromechanics Framework: Where We Stand and What's Next

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Abstract

Under high heat fluxes, most pyrolyzing materials exhibit a two-stage deformation behavior: an initial swelling phase, followed by shrinkage. Swelling arises from the buildup of internal gas pressure within closed or partially obstructed pores, leading to local inflation and volumetric expansion. In contrast, shrinkage results from the thermo-chemical reorganization of the polymer matrix, as organic chains condense into more ordered, pseudo-graphitic char structures.

In wood, for example, the second phase dominates, with an overall volume loss of about 50 percent observed after complete pyrolysis. Conversely, in materials such as cork and RTV silicones, swelling prevails. For composite materials, the overall behavior depends strongly on the fiber architecture, matrix chemistry, and degree of confinement, leading to a broad range of deformation responses.

A detailed anisotropic elastic solid mechanics model has been developed within PATO's pyrolysis framework to capture these coupled mechanisms. The model accounts for the interactions between internal gas pressure, pyrolysis progression, and solid matrix deformation, offering a unified description of swelling and shrinkage phenomena. When applied to wood and carbon–phenolic composites, the model shows promising predictive capabilities.

New input parameters are required to inform this model, including mechanical moduli (Young's modulus, Poisson's ratio, etc.) measured at different stages of decomposition—or at least in the virgin and charred states—to enable the use of standard interpolation schemes. Ongoing developments aim to improve the constitutive laws to include cracking, damage evolution, and plasticity, thereby enhancing the model's robustness and predictive fidelity for ablative and porous thermal protection materials under extreme environments.

Keywords: Pyrolysis, modeling, simulation.

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Response of Carbon-Phenolic Ablators and Preforms to Combustion

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[b]*National Center for Supercomputing Applications, University of Illinois Urbana–Champaign, Urbana, IL 61820, USA*

Abstract

Carbon-phenolic ablators, a common material for hypersonic thermal protection system (TPS), are exposed to a post-combustion flow [1–4]. This is done to characterize ablation to assess suitability of this TPS class in hypersonic air-breathing engines, which is an area of active research [5, 6].

Carbon-phenolics are produced using a carbon-bonded carbon preform derived from rayon (CeraMaterials), which is infiltrated according to the HARLEM process [7]. Test specimens of both preform and the composite are exposed to a combustion product stream generated by a McKenna Burner (Houlthuis and Associates), which produces an axisymmetric quasi-flat flame [8]. This burner is widely used in diagnostic development applications, making it a good starting point for use in laboratory ablator investigations [9, 10]. Flames used have equivalence ratios that range from oxidizing (lean) to oxidation-suppressed (rich).

Photogrammetric recession measurements suggest that in-depth oxidation is a significant mechanism of material degradation, with the estimated mass loss from the change in bulk volume being approximately half of the measured mass loss in a rayon sample exposed for 20 minutes under oxidizing conditions. Mass loss measurements (figure 1) demonstrate a clear oxidation resistance for carbon-phenolic ablators, compared to the rayon preform. This is determined by subtracting the mass loss expected due to pyrolysis from the absolute mass loss of a carbon phenolic ablator, with the resulting value being attributed to oxidation; the amount attributed to oxidation is consistently lower than the rayon mass loss. Scanning electron microscopy suggests a preferential oxidation of the charred matrix in carbon-phenolic ablators compared to the fiber phase. Figures 2–4 show the material before and after ablation.

Keywords: Carbon-phenolic ablator, microstructure, combustion, oxidation

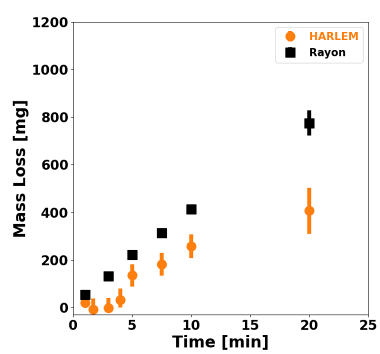

Figure 1: Mass loss history from oxidation

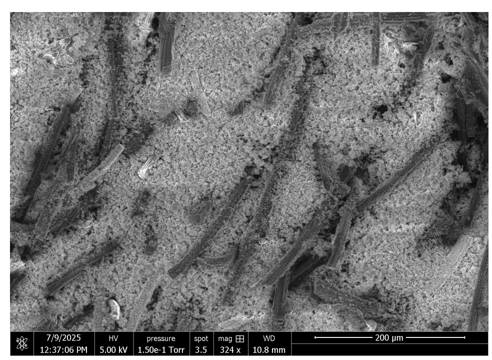

Figure 2: Virgin HARLEM

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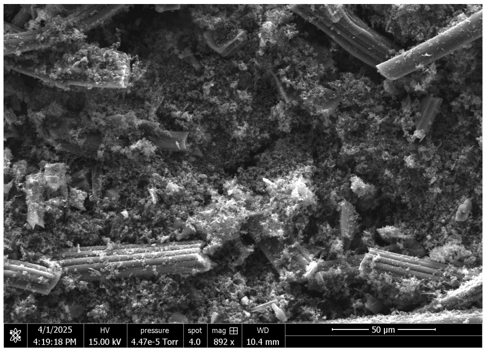

Figure 3: Stoichiometric combustion HARLEM

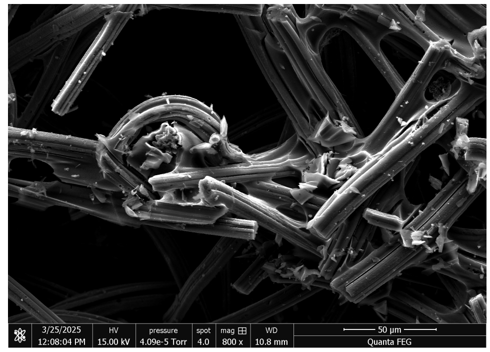

Figure 4: Oxidized (lean combustion) HARLEM

Acknowledgements

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AI-experiment-theory intergrated analysis of the role of molecular structure in determining char yield of ablative polymers

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Abstract

As the spacecraft explores the extended territory of the solar system, polymeric ablative materials (PAM) for spacecraft thermal protection systems are needed to offer improved heat dissipation with higher char yield (Y_C). This study aims to understand the structure-property relationship that determines Y_C in PAM, through a comparison between phenolic resin (PR) and poly(p-phenylene oxide) (PPO), which have similar molecular structures but significantly different Y_C (55 wt.% for PR and 25 wt.% for PPO, see Figure 1). First, a graph neural network (GNN) was developed to predict polymer Y_C and statistically assess how individual bonds influence it. The model suggested that PPO's low Y_C originates from its para-substituted configuration and additional methyl groups attached to the aromatic ring. Second, pyrolysis experiments using Py-GC/MS showed that PR generates tricyclic compounds during decomposition, whereas PPO does not, suggesting that PPO's lower Y_C yield may be due to its inability to form polycyclic aggregates. Next, theoretical analysis of PR and PPO pyrolysis mechanisms indicated that PPO's para-substitution raises the energy barrier for tricyclic formation. Furthermore, the methyl groups fail to assist cyclization because they are spatially distant from neighboring aromatic rings, collectively reducing tricyclic yield. Molecular dynamics simulations confirmed that early-stage tricyclics accelerate char precursor growth, accounting for PR's higher Y_C compared to PPO. These integrated insights into structure-property relationships will aid the design of new PAMs with enhanced thermal protection.

Keywords: Polymer, pyrolysis, char yield, density functional theory, molecular dynamics simulation

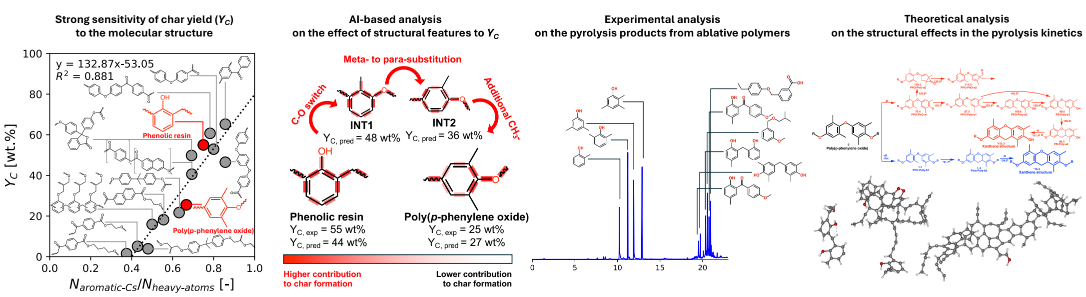

Figure 1: Schematic of AI-experiment-theory analysis for providing the detailed understanding of the structural effects in the Y_C of polymers.

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Graphite Ablation: A Review of Theory and Comprehensive Comparison of Experimental Data

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Abstract

For decades, graphite has served as a workhorse material across multiple engineering disciplines in which heterogeneous reactions of high temperature carbon are of interest. Graphite provides researchers with an abundant proxy for carbon-based composites allowing the rapid collection of large experimental data sets revealing ablative behaviors and the determination of chemical kinetic rates. However, a risk becomes posed when graphite data is relied upon for the development of empirical carbon ablation models. This risk is made evident when mass loss derived reaction rates are compared between studies revealing orders of magnitude variation due to the equal variability between the graphites selected for testing (in terms of purity level, grain size, and porosity) and the experimental methods (pressure, reactant concentration, convective and diffusive limitations).

Systematic categorization of graphite ablation data is crucial to determine the degree of confidence to be placed in predictive methods derived from such results. This is an ongoing process with contributions from many researchers including most notably L.L. Perini [1] and C. Park [2]. Presently, a new model is developed using contemporary and legacy data. Validated theoretical developments for graphite ablation under reaction rate limited, transitionary, diffusion limited, and sublimation regimes are augmented by a boundary-layer solution for heterogeneous reactions coupled to finite-rate surface kinetics [3]. The goal is to normalize all available graphite ablation data under hypersonic flight relevant conditions using a non-dimensional ablation rate that accurately accounts for differences in mass transfer and is discriminated by groups of similar graphite materials.

Keywords: Graphite, Damköhler number, non-dimensional ablation rate B', carbon, oxidation, sublimation

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Subsonic Boundary Condition for ICP Wind Tunnel Simulations

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Abstract

A subsonic inlet boundary condition based on the method of Poinsot and Lele [1] was developed to model typical ICP wind tunnel flows. Mass flow rate and total enthalpy are held constant on the boundary while all other flow properties are computed on the boundary by solving the same conservation equations as in the domain while taking into account the incoming waves from the interior of the domain. Thermochemical equilibrium is enforced on the boundary and in order the stabilize the flow under low velocity conditions an artificially high farfield velocity is imposed. The distance between the inlet boundary and the sample is set to match the distance between the ICP wind tunnel nozzle exit and sample in a particular experimental configuration. The boundary condition has been tested on multiple experimental conflagrations pertaining to those of the plasmatron facility at VKI and the Plasmatron X facility at the University of Illinois at Urbana Champaign. Figure 1 below shows the temperature flowfield for a nominal 45 MJ/kg, 16 g/s air test condition corresponding to the experiments conducted by Fagnani *et al.* [2].

Keywords: Subsonic, ICP, Ablation, CFD, Boundary Conditions

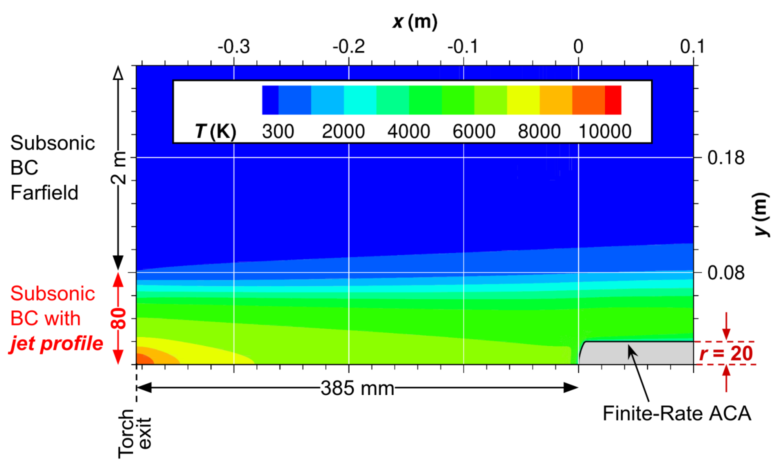

Figure 1: ICP wind tunnel simulation with subsonic inlet jet profile boundary condition and 20 mm radius iso-Q ablating test sample showing contours of temperature for a nominally 45 MJ/kg, 16 g/s air test condition based on the experiments conducted by Fagnani *et al.* [2].

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Experimental Verification of Calibration Based Approach to Determine Inverse Heat Transfer Material Parameters

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Abstract

Thin film gauges (TFGs) are a class of resistance temperature detectors which operate at ultra high frequencies [1][2][3]. They have been utilized for many years in conjunction with inverse heat transfer theory to calculate surface level heat flux histories in hypersonic ground testing facilities [4][5].

TFGs with a silver sensing element and Macor substrate material have been manufactured in house at the NMSU Micro Imaging Core Suite (MICS) by means of sputtering (fig 2). Passive oxidation of the sensing element from day to day causes frequent static calibration drift which, in turn, makes reliable temperature measurements impossible. It is the goal of the work at hand to demonstrate that the theoretical groundwork laid in ref [6] can be experimentally verified, and moreover that heat flux can be reliably calculated from raw voltage and time data without knowing the temperature of the sensor by means of a dynamic laser calibration. The theory in this work can be extended to TFGs which have lost their calibration due to damage sustained in shock tunnels as a metric for monitoring sensor health.

Bulk Macor thermophysical properties were measured to a high accuracy in a Thermtest MP-1 transient plane source. Ordinarily, TFGs must undergo a static calibration where resistance is carefully measured over a temperature range to be able to relate the raw measured voltage (generated from a known, small input excitation current) to temperature. The static calibration parameters including the temperature coefficient of resistance (TCR), reference resistance (resistance at a known temperature), as well as the spectral absorptivity were considered unknowns. A known step shaped heating pulse was imposed upon the TFG by a Laserline LDM 1500-60 near-infrared (980-1020nm) laser (fig 1) housed in the NMSU hypersonic research center. Both the laser heat flux and the TFG voltage response were recorded. The known heat flux and voltage were used in a least-squares nonlinear curve fitting algorithm to iteratively solve for the unknown bulk parameter, equal to the product of TCR and spectral absorptivity. The original heating pulse was recalculated using the least squares parameters (fig 3a). The inverse equation relating voltage to heat flux was obtained from rewriting the preconditioned inverse heat conduction equation from ref [7] in terms of voltage:

$$\int_{u=0}^{t} V^{*}(u)du = \frac{2AV_{ref}}{\beta_{ss}\sqrt{\pi}} \int_{u=0}^{t} q_{L}''(u)\sqrt{(t-u)}du, t \geq 0 \tag{1}$$

where $A = TCR * \alpha_\lambda$ is the bulk least-squares parameter, α_λ is the spectral absorptivity of the TFG surface at a fixed angle of incidence and at 1020 nm laser wavelength, V^* is the voltage rise from initial, V_{ref} is the TFG voltage at room temperature, β_{ss} is the thermal effusivity of the TFG substrate, and q_L'' is the laser heat flux. Heat flux predictions were stabilized via the future time method [7]. A second, more complicated heating profile was later tested and, using the same least squares parameters calculated from the first pulse, was also reconstructed (fig 3b). The reconstructed heat flux shows good agreement with the input values.

Keywords: hypersonics, temperature sensor, inverse heat conduction, heat flux, calibration

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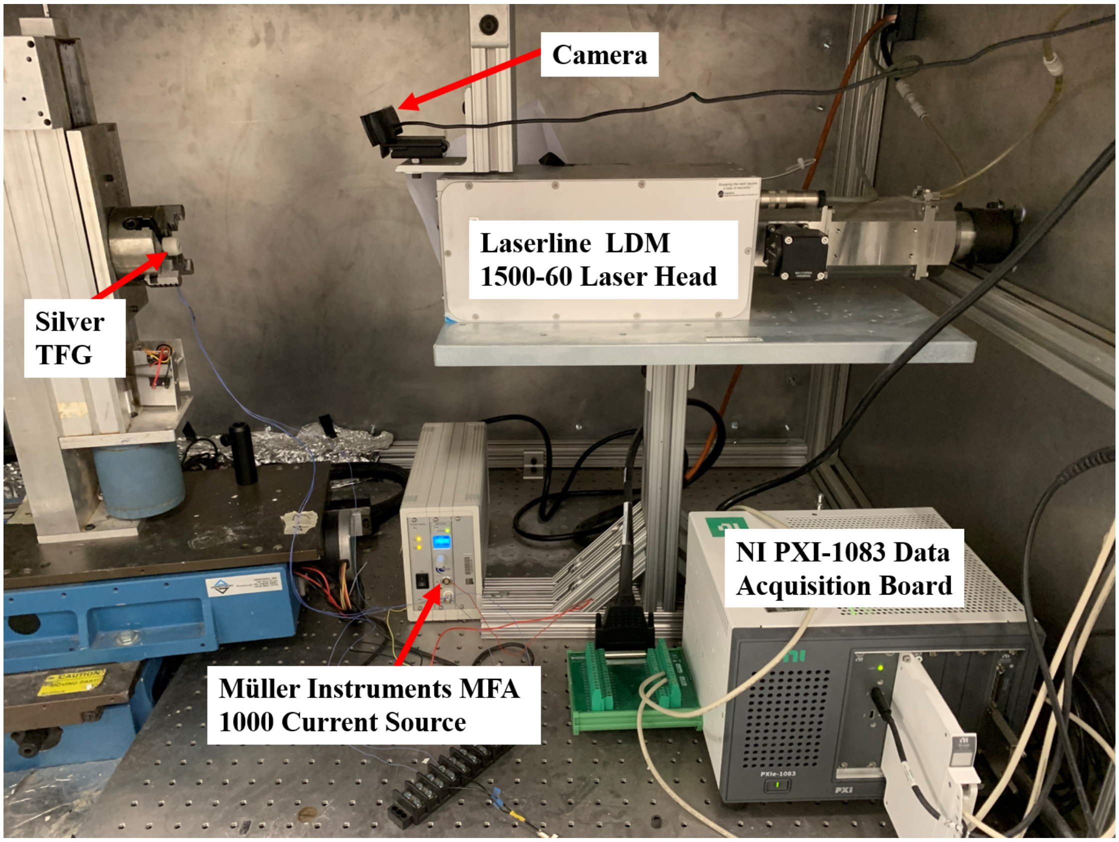


Figure 1: Laser heating test setup.

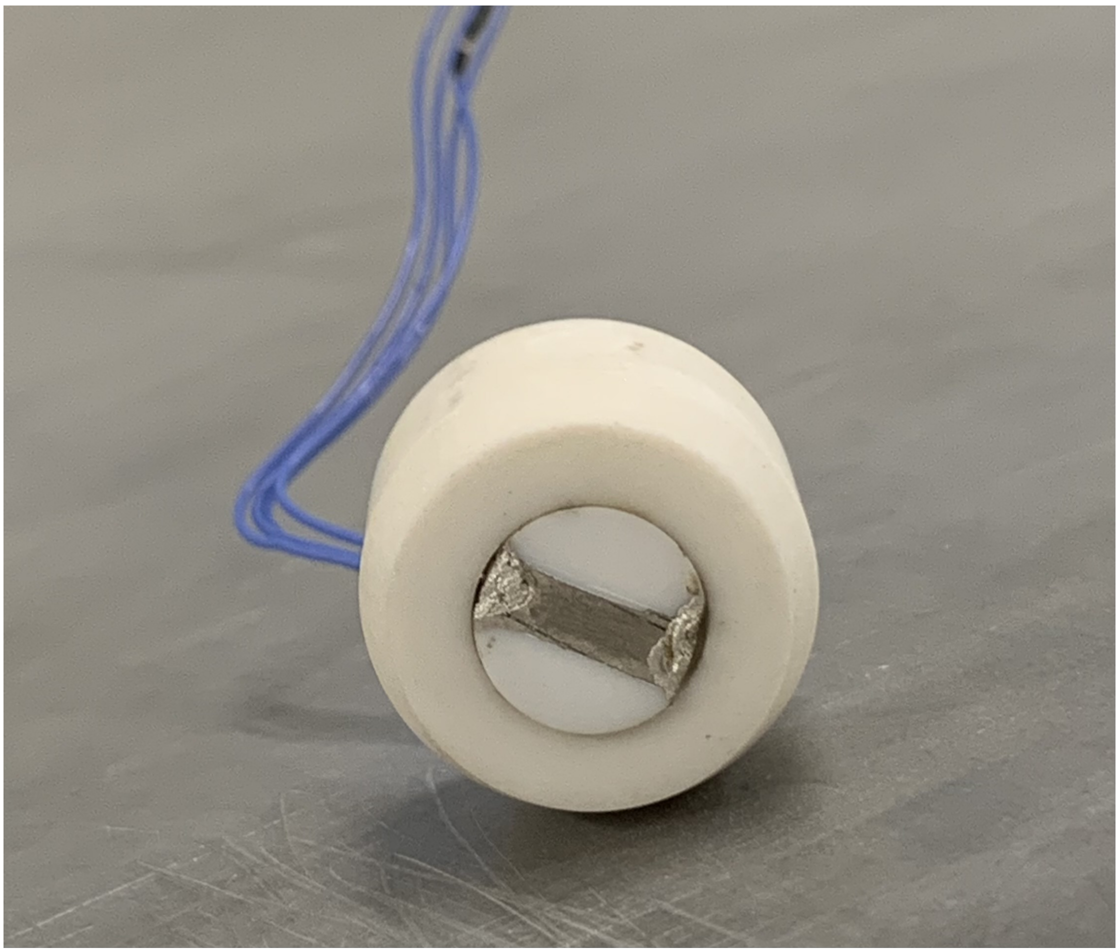
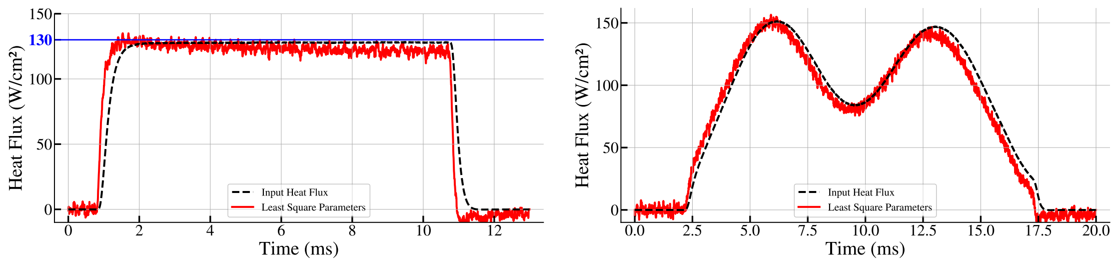


Figure 2: Silver TFG sensor.

3



(a) Calibration pulse reconstruction.

(b) Heat flux reconstruction using calibration parameters.

Figure 3

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Study of the passive to active transition of SiC in the atmospheric pressure UT Austin ICP torch via PLIF measurements of Si and SiO

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Abstract

While the development and validation of high fidelity air-carbon chemistry models has received substantial attention recently, progress on the development of an air-carbon-silicon analog has been limited due to a lack of chemical species experimental data at flight relevant conditions and the complex physics associated with the passive to active transition of silicon carbide based materials.

Here we present planar laser induced fluorescence measurements, made in the atmospheric pressure UT Austin ICP torch, of atomic Si and SiO in the boundary layer of SiC based materials as they transition from the passive condition. Two material types were tested over the course of this work, monolithic SiC pucks and SiC coated graphite iso-qs.

Both the appearance of atomic Si and SiO emission in the data is clearly associated with a visual change in surface morphology, indicating the onset of transition from the passive condition. Linking the appearance of Si and SiO emission to surface pyrometry data provides an estimate of the transition temperature, which agrees with literature values for SiC at 1 atm. A standoff in atomic Si emission from the surface suggests surface production of SiO is dominant at our conditions, with the subsequent dissociation of SiO in the gas phase leading to the strong Si emission away from the wall. Silica melt bubbles persist on the material surface through all tests, indicating our measurements pertain to a transitional regime between the passive and fully active conditions for SiC. Follow-on measurements are planned to better quantify the SiC regime.

Keywords: SiC, PLIF, passive to active transition, Si, SiO.

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Surface Temperature Field Measurement Using Thermographic Phosphor Thermometry

Andrea Gallegos Quintana, Allianna R. Chavez, Shabnam Mohammadshahi

In recent years there has been an increased interest in high-speed, high-temperature supersonic, and hypersonic flows for problems studying reentry and hypersonic vehicles. Thermographic Phosphor Thermometry (TPT) can be used to obtain experimental temperature results with high spatiotemporal resolution. TPT is a non-contact luminescence-based method that uses phosphor materials that emit temperature-dependent light when excited by ultraviolet radiation, allowing for accurate, full-field surface temperature measurements. Upon excitation, these materials emit light whose intensity, wavelength, or decay time varies predictably with temperature. Among these techniques, lifetime-based TPT is especially advantageous due to its immunity to excitation inhomogeneity, variation in coating thickness, and optical access angle. We applied Magnesium Fluorogermanate particles with hydroxypropyl cellulose (HPC) binder on aluminum plate and perform calibration using a 385 nm UV-LED and a high-speed camera to find the lifetime-temperature correlation. This work proposes to study the challenges required in adapting future TPT to hypersonic environments.

Acknowledgment: This research is based upon work supported by the New Mexico NASA EPSCoR Research Infrastructure Development (RID) Program through the National Aeronautics and Space Administration under NASA Cooperative Agreement No. NM-80NSSC22M0044.

Investigation of spallation and volumetric ablation in TPS materials through plasma facility experiments

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Abstract

Ablative thermal protection systems mitigate thermal energy transport to space vehicles through material removal processes. These processes occur through a wide variety of mechanisms, both chemical and mechanical. In order to better understand in-depth material changes due to volumetric ablation, previously tested samples were re-exposed to a pure oxygen environment in the High Enthalpy Low-Cost Multi-Use Torch (HELMUT) facility at the University of Kentucky [1] [2]. Additionally, PICA samples were tested to investigate the impact phenolic resin has on the material response. Scanning electron microscopy (SEM) was conducted on disconnected fibers that remained on the samples after flow exposure to investigate in-depth fiber and binder pitting. Material response across test campaigns was compared to evaluate changes in structural integrity caused by in-depth oxidation, which is suspected to affect spallation behavior. Re-exposure produced higher percent volume loss, greater percent mass loss, and a reduction in density. PICA samples produced a negligible fiber layer, and a lower percent volume loss. These findings indicate that FiberForm tested in the HELMUT facility could be operating in a reaction-limited regime, with substantial oxygen penetration beneath the surface. This methodology also establishes a framework for providing degree of char estimates for material response models, and highlights the role phenolic resin has on structural integrity.

Keywords: oxidation, spallation, volumetric ablation

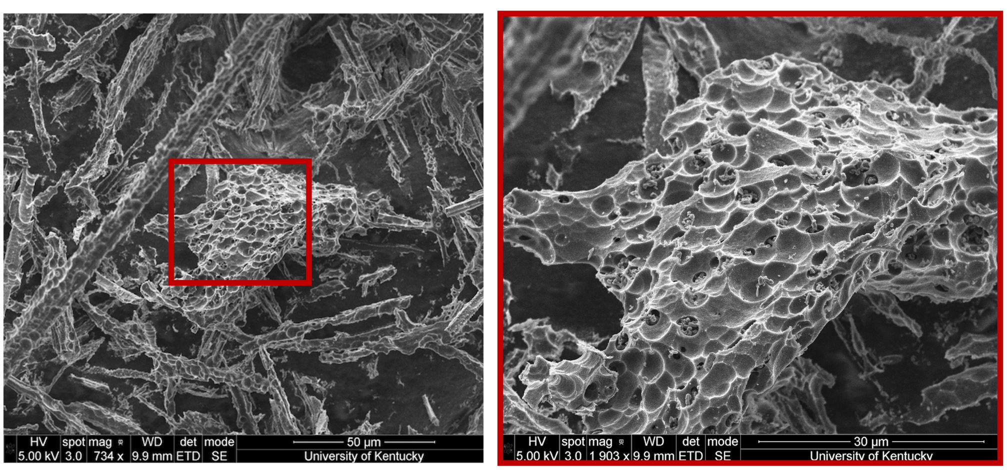

Figure 1: Scanning electron microscopy (SEM) images of fibers captured during HELMUT tests.

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Tomography And Lattice Boltzmann Exploration (I): Image Segmentation

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Abstract

Computed Tomography (CT) and the segmentation of material microstructures provide valuable insights that can be directly linked to their physical properties and performance [1, 2]. Deep learning-based segmentation is increasingly explored in material engineering as an alternative to traditional thresholding or labor-intensive segmentation methods.

In this work, we investigate two segmentation frameworks: one using the commercial Dragonfly software and another based on a custom implementation in PyTorch.

The Porous Microstructure Analysis (PuMA) tool has been used to generate geometries such as Triply Periodic Minimal Surfaces (TPMS, Fig. 1) and fiber domains resembling FiberForm. These synthetic geometries were 3D printed, CT scanned and analyzed to provide reference datasets for validating both the Dragonfly workflow and our custom pipeline.

The developed pipeline employs a custom deep learning architecture based on the U-Net model (Fig. 2) [3], which has been trained to capture the unique structural and morphological characteristics of CT scans taken from Thermal Protection System (TPS) material samples.

The segmentation separates fiber-based materials (Fig. 3a) into distinct classes, namely fibers and voids (Fig. 3b). These results enable the construction of realistic digital geometries that can be used in computational simulations to evaluate flow behavior and extract effective properties such as permeability [4].

By integrating CT-based feature extraction, geometry reconstruction, and permeability assessment, the proposed framework establishes a robust and automated workflow for TPS material characterization, supporting their qualification and design in aerospace applications.

Keywords: segmentation, deep learning, porous material

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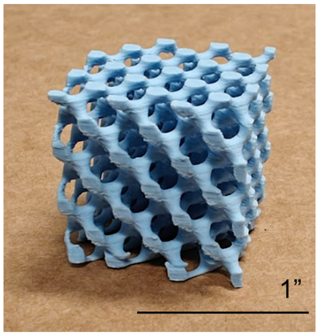
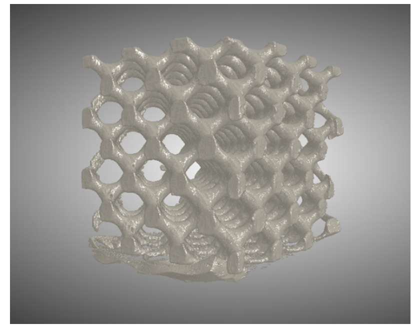


(a) 3D printed structure



(b) Segmented dataset from Dragonfly

Figure 1: TPMS structure used for validation

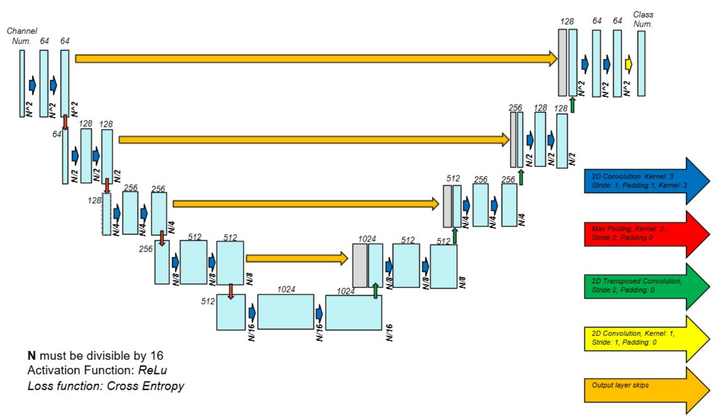
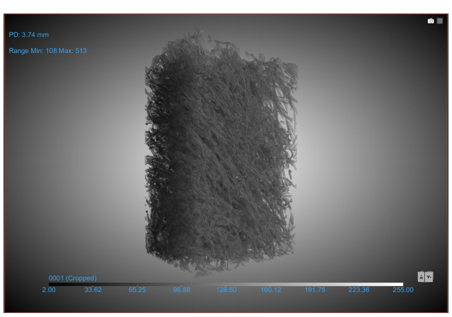
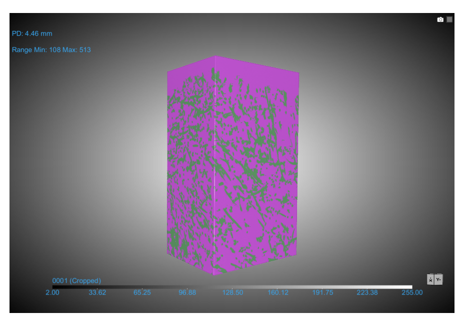


Figure 2: U-net structure



(a) Cropped raw data before segmentation.



(b) Segmented dataset using a U-Net model and trained using manually segmented layers within the data.

Figure 3: Example of segmented material using Dragonfly.

2

Modeling spalled particles in the HyMETS arc jet using a modified dissipation sensor

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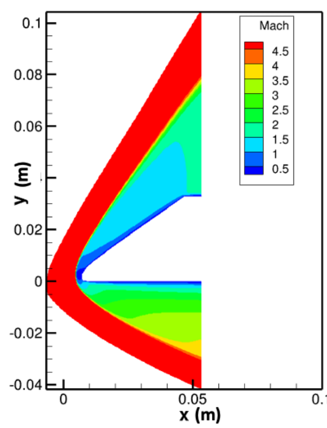
Abstract

Ablative thermal protection systems (TPS) are used to shield internal components of space vehicles from intense heating during atmospheric descent. Mass loss of ablators due to the ejection of particles from the bulk material is known as spallation. Previously, various tests were conducted at NASA's Hypersonic Materials Environmental Test System (HyMETS) facility [1]. High-speed images, particle tracking velocimetry analysis, facility measurements, and the Kentucky Aerothermodynamics and Thermal-response System (KATS) have been used to develop models of the HyMETS samples. Additional work has been conducted on the modification of numerical dissipation in the KATS fluid dynamics solver (KATS-FD). When solving inviscid flux vectors, instability can occur across discontinuities. In order to correct for these problems, a modified version of the Ducros sensor proposed by Hendrickson et al. was implemented into KATS-FD [2]. Work has thus far focused on wedge samples to investigate the impact of shear. Preliminary results indicate that peak particle generation coincides with maximum heating and occurs slightly offset from peak shearing. This data has been analyzed for the development of an empirical model to couple with material response solvers in order to more accurately predict ablation in TPS materials.

Keywords: spallation, numerical dissipation, computational fluid dynamics

(a) Facility Image



(b) Sample CFD

Figure 1: HyMETS facility image of spallation seen on a wedge sample (a), and the corresponding cfd solution of the sample halfway through the test (b).

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Tomography And Lattice Boltzmann Exploration (II): flow through porous media using LBM

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Abstract

Accurate prediction of permeability in porous materials is critical for thermal protection systems (TPS), since it governs the transport of pyrolysis gases and influences the overall ablation response. Traditional computational methods for obtaining permeability, such as the Stokes flow approximation and DSMC, rely on restrictive fluid assumptions or are computationally expensive. The Lattice–Boltzmann Method (LBM) provides an efficient alternative for simulating low-speed flows in continuum and near-continuum regimes and complex geometries, including porous media [1]. In LBM, the velocity space is discretized into a finite set of directions (e.g., 9 for 2D or 27 for 3D), which reduces computational cost compared to DSMC. LBM calculates an equilibrium distribution function to stream particles to neighboring lattice nodes as seen in Eq. (1). Collisions with walls are simulated using bounce-back conditions, which enforce fluid interactions with solid and porous field points.

$$f_\alpha(\mathbf{x} + \mathbf{e}_\alpha \delta t,\ t + \delta t) - f_\alpha(\mathbf{x}, t) = -\frac{1}{\tau}\left[f_\alpha(\mathbf{x}, t) - f_\alpha^{eq}(\mathbf{x}, t)\right] \tag{1}$$

The purpose of this project is to derive the permeability tensor for porous media, such as carbon fiber preforms, used in thermal protection systems. The geometries will be obtained from micro-computed tomography measurements. Permeability is treated as an effective property in Darcy's law Eq. (2), enabling macroscopic modeling of flow through complex pore structures.

$$k = -\frac{\mu U}{\left(\frac{dP}{dx}\right)} \tag{2}$$

An existing Fortran code [2] is being used to simulate these complex geometries at the pore scale, while a new Python code is being developed for 2D proof-of-concept studies.

Verification was first conducted on a lid-driven cavity, showing excellent agreement with benchmark data from Hou et al.[3]. Moving towards simulating porous media, a typical test case is to simulate the flow through periodic cylinder arrays [1, 4], which introduced new challenges in boundary conditions. Fig. 2 shows the validation test case developed in Python.

These preliminary results are a stepping stone towards more complex porous media simulations in a 3D LBM framework. The next steps include integrating segmented porous test samples and validating permeability estimations with experimentally obtained data.

Future extensions will incorporate heat transfer and multi-species flow to more accurately capture the coupled physics relevant to ablative TPS.

Keywords: permeability, porous media, thermal protection systems

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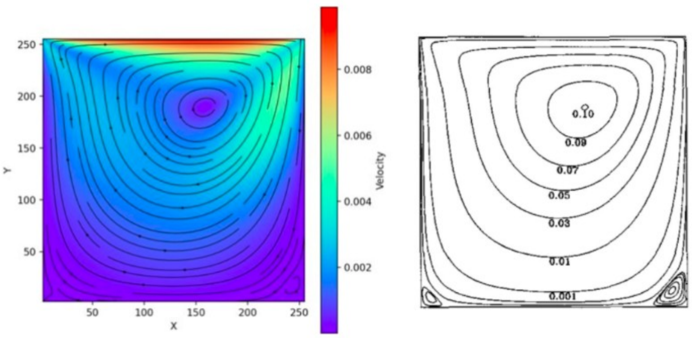

Figure 1: Comparison of velocity magnitude and streamlines with [3] for Re=100.

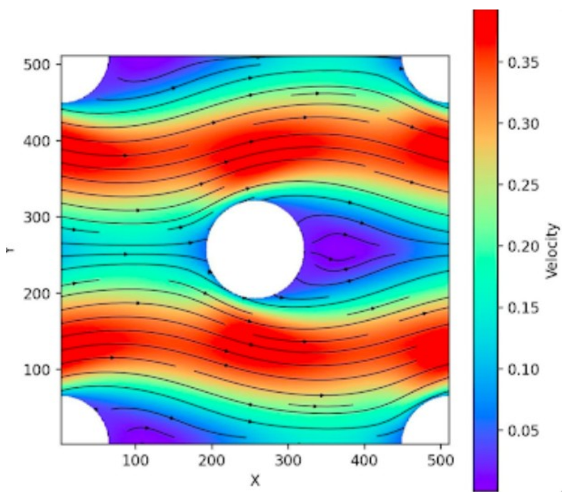

Figure 2: 2D Simulation of pillar array with periodic B.C. in each direction with applied body force to simulate pressure gradient.

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Determination of Thermal Conductivity of Syntactic Foams with Transient Plane Source Technique

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Abstract

Syntactic foams are lightweight composite materials made of a polymer or matrix filled with hollow microspheres. This material is recognized for its low density and excellent thermal insulating properties.

In this work, we investigate the thermal properties of syntactic foams using the Transient Plane Source (TP) method and analyze their microstructure using an optical microscope and micro-computed tomography.

The TP experiments were carried out using a ThermTest MP-1 measurement platform (Fig. 1a). This technique uses a symmetric sensor configuration to generate a heat flux while measuring the rise in temperature. The power and duration of the pulse are user parameters that need to be estimated depending on the type of material. A Python GUI was developed to estimate those parameters based on prior knowledge of the material to automate this process. This code applies the rules-of-thumb provided in Gustafsson [1] derived from an analytical solution to the heat transfer problem. We have performed preliminary testing using five syntactic foam samples with densities ranging from 0.26 to 0.46 $\mathrm{g\,cm^{-3}}$, placed under multiple power and test duration conditions. The results showed consistent thermal conductivity values between 0.071 and 0.082 $\mathrm{W\,m^{-1}\,K^{-1}}$ (Fig. 1b), and thermal diffusivity values between 0.17 and 0.19 $\mathrm{mm^2\,s^{-1}}$, demonstrating the insulating character of syntactic foams.

Furthermore, analysis of the internal microstructure through CT segmentation (Fig. 2) provides quantitative volume fractions of fibers, resin, microspheres, and voids. These experiments were carried out at NMSU using a Waygate Systems Phoenix V. The qualitative knowledge of the internal structure helps explain material performance. Observing the material's internal structure helps to assess quality control and ensure consistent material batches. Additionally, we can compute effective properties based on the components and the porous structure. For example, knowledge of the thermal conductivity of the individual components would allow us to perform numerical simulations of heat transfer, which would enable us to determine the effective thermal conductivity. These values can be compared with the experimental results of the transient plane source.

This study shows the potential of the TP technique as a reliable and quick tool for measuring thermal properties of syntactic foams. It gives a basis for future work on anisotropic analysis and thermal degradation studies.

Keywords: hypersonics, ablation, material modeling, thermal conductivity, tomography

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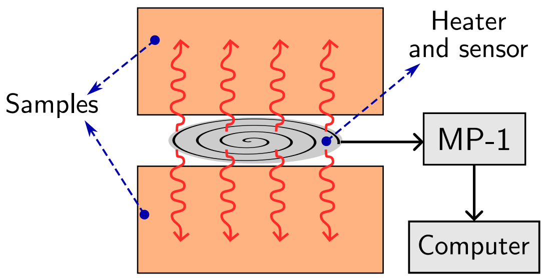
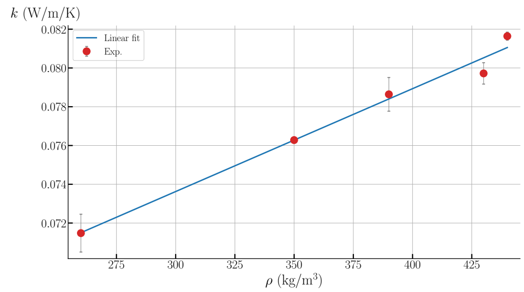
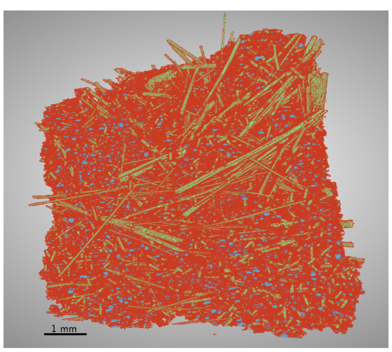


(a) Schematic of the Transient Plane Source (TPS) method using the MP-1 instrument, where the flat sensor works simultaneously as heater and thermometer, placed between two identical samples.

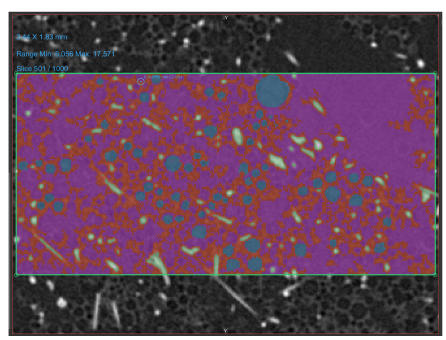


(b) Experimental relationship between thermal conductivity (k) and density of the samples. Errorbars represent the std. of 5 repetitions of the measurement. Linear fit: $k = 5.31 \cdot 10^{-5}\rho + 0.05771$, and $R^2 = 0.98287$.

Figure 1: Integration of the TPS experimental configuration with resulting thermal data provides a clear demonstration of how the MP-1 is a reliable tool for accurate characterization of material thermal properties.



(a) X-ray CT scan of the Syncfoam sample reconstructed in Dragonfly, showing open porosity (blue), embedded glass fibers (green) suspended within the foam matrix (red) and preferentially aligned in the horizontal direction.



(b) Manually segmented 2D slice of the Syncfoam material used as training data for Dragonfly's AI segmentation workflow. Classes are defined as blue = enclosed volumes, green = glass fibers, red = foam matrix, and purple = open volume (air).

Figure 2: CT imaging and segmentation of Syncfoam enable quantitative characterization of fiber alignment, porosity, and material distribution, which are critical microstructural parameters for predicting and modeling electrical conductivity in glass-fiber foams.

2

Towards Modeling of RTV Intumescence in PATO

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Abstract

Room temperature vulcanizing (RTV) silicone is a high-temperature adhesive used as a gap-filler between ablative heatshields tiles in numerous entry missions. The intumescence, or swelling with exposure to heat, of RTV is a well-known effect that, combined with differential recession could cause the gap filler to protrude past the ablator surface and form a "fence". Fencing of RTV can then cause the flow around the heatshield to transition to turbulence which could lead to augmented heating on the entire heatshield.

Past experiments conducted at the Plasmatron X facility at high enthalpies have shown significant fencing of the RTV in both nitrogen and air plasmas [1,2]. Further experiments in a more controlled heating environment, performed at the Advanced Light Source (ALS), beamline 8.3.2 using *in situ* X-ray micro-computed tomography under heating, showed heating rate-dependent swelling and shrinkage of the RTV [3–5].

Building on these experimental insights, we used previously determined RTV properties [6,7] to simulate the ALS setup in PATO [8]. The thermal response of RTV from PATO was compared with thermocouple data from experiments. Swelling of RTV was also simulated using the new incremental approach in PATO for modeling deformation due to solid mechanics [9] and was compared against *in situ* Micro-CT data. Results showed good agreement of fence height and thermal profiles at all heating rates and indicated that the key factor contributing to RTV swelling is the internal pressure build-up within the material. As RTV is initially cured into a low-porosity, low-permeability compound, increase in temperature and pyrolysis gas production causes a significant increase in internal pressure, causing a pronounced volume increase. Accounting for changes in porosity, permeability and other key material properties allowed for capturing the RTV volume change. This capability shall be further expanded to model the Plasmatron X experiments in the future. By accurately capturing RTV swelling mechanisms, this work enables higher-fidelity prediction of gap-filler behavior during atmospheric entry, directly addressing a critical risk for spacecraft heatshields.

Keywords: *RTV, material response, intumescence, in situ MicroCT, TPS, Material response modeling, PATO*

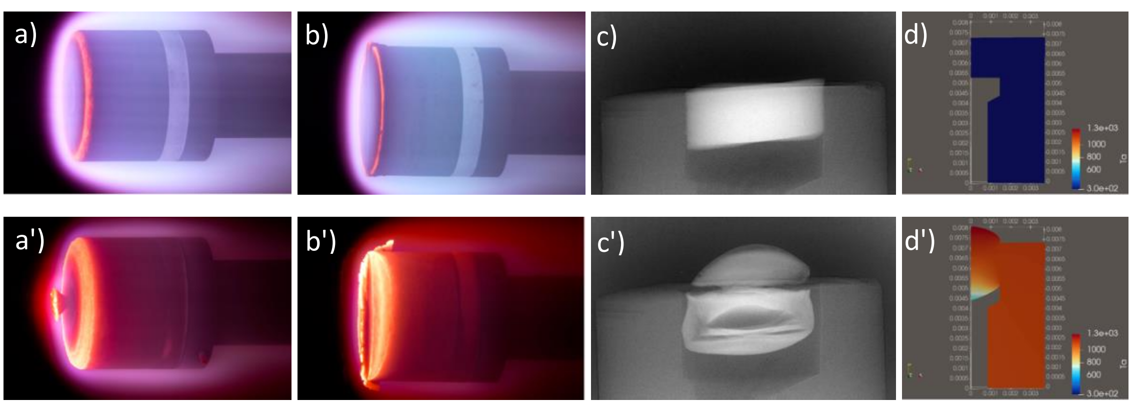

Figure 1: Images from high enthalpy testing in N_2 plasma of an RTV cylinder at the (a) start and (a') end of test, and an RTV slot at the (b) start and (b') end of test, along with *in situ* heating and radiography at the ALS at 2000°C/min in Argon at the (c) start and (c') end of test, and temperature contours from a PATO simulation of the experiment in (c-c') at the (d) start and (d') end of the simulation.

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Re-radiation model in the Unified Solver

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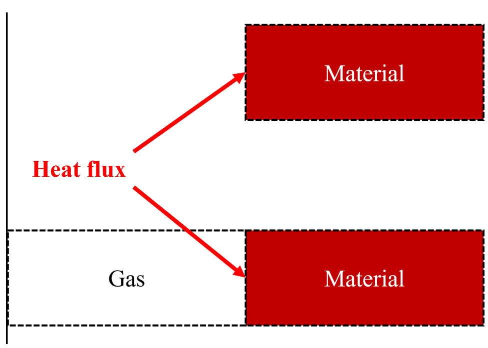
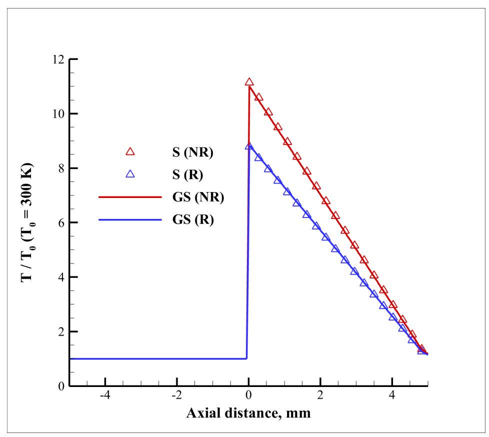
Abstract

Modeling the interaction between the material and gas phase has been the one of the main interests in thermal protection system. Re-radiation is one of the key factors needed to be considered to predict this interaction accurately. Re-radiation is one of the most important mode of heat rejection for Thermal Protection System (TPS) material, and it is normally modeled by imposing Stefan-Boltzmann law at the surface of domain. However, it is impossible to apply Stefan-Boltzmann law in the unified solver as it does not have boundary face at the interface between the material and gas region. As an alternative way, Radiative Transfer Equation (RTE) can be a solution [1]. However, coupling with RTE code with unified solver requires extremely expensive computational cost, therefore, similar to the way that Schrooyen [2] have used in his work is used to apply Stefan-Boltzmann law at the interface to solve this issue. The re-radiation model in the unified solver is used to conduct the verification test, and the results are compared with the results of only solid case.

Keywords: Stefan-Boltzmann law, Re-radiation model, Unified Solver.



(a) Test illustration



(b) Test result (S : solid case, GS : gas-solid case, R : radiation, NR : no radiation)

Figure 1: Verification test.

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Estimation of evaporation and sublimation rates of a phase-change material in post-hypersonic shock conditions

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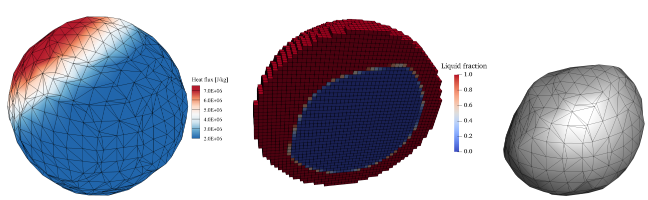
Abstract

When quiescent atmospheric ice particles receive heat flux from a post-hypersonic shock region, partial mass loss induced by phase-change processes is a possible scenario. A computational framework is under development to provide the thermal-fluidic response for the phase-change material (PCM). The main objective of this work is to compute evaporation and sublimation rates as the initial solid domain melts into arbitrary shapes. The melting process is numerically calculated by the total enthalpy-based lattice Boltzmann model (ELBM) proposed by Huang and Wu (2015) [1], where the collision term is modeled according to Gaedtke *et al* (2020) [2]. Once a partial fraction of the initial volume of ice becomes unity, evaporation rates are estimated through the Hertz-Knudsen law. The Hertz-Knudsen law depends on the ice surface temperature, the equilibrium vapor pressure, and the local flow-field pressure. An example of how the initial geometry changes upon an imposed heat flux is given in Fig. 1, where Fig. 1a shows the heat flux applied at the discretized domain for the ELBM solver. After a total elapsed time t_1, the PCM partially melts. The resulting liquid fraction is shown in Fig. 1b, the new solid geometry shown in Fig. 1c. Estimating the evaporation and sublimation rates will determine how the interface in the liquid region evolves, thereby affecting the overall melting process.

Keywords: Mass removal, evaporation and sublimation, post-shock conditions, framework development



(a) Constant incident heat flux. (b) Liquid fraction at t_1. (c) New surface at t_1.

Figure 1: Evolution of geometry change caused by phase-change.

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Modeling of a high velocity oxygen fuel (HVOF) torch

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Abstract

High velocity oxygen fuel (HVOF) is a thermal spray method noted for its high velocities and relatively high temperatures, and is most often used to form uniform, low porosity coatings. It is being investigated as a quick and cost-effective method for testing a large volume of materials under hypersonic conditions. A model of the HVOF torch process is being developed with Ansys Fluent to aid in this endeavor. Using the energy, RNG k-ε, and species transport models with eddy-dissipation turbulence-chemistry interaction and a single-stage complete propane combustion mechanism, the Fluent model reproduces empirical stagnation total pressure values, provided by Johns Hopkins University Applied Physics Laboratory (APL), to within 1.5psi, shown in Fig. 1, while slightly overestimating the stagnation heat flux. A multi-step reaction mechanism accounting for incomplete combustion, oxidation, and high-temperature product dissociation should lower the heat flux while minimally affecting the pressure. Cheng et al. [1] and Ren et al. [2] have demonstrated an expanded combustion mechanism with dissociated products will lower the resulting heat flux due to the increased energy usage. Once these complex Arrhenius kinetics are accounted for, this model will expand the screening process of materials under hypersonic conditions.

Keywords: High velocity oxygen fuel, combustion, thermal spray, Ansys Fluent

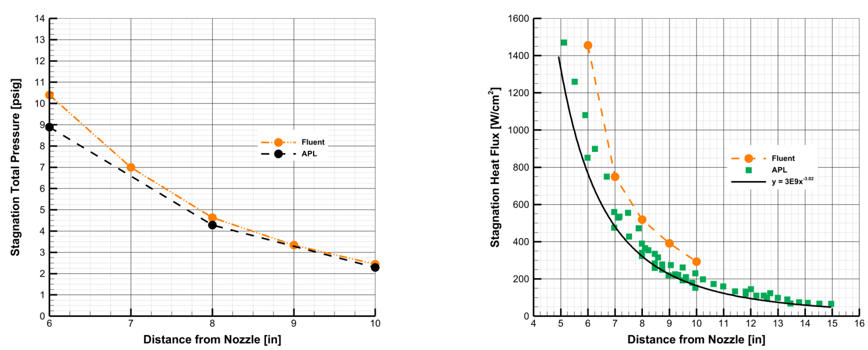

Figure 1: Validation total pressure and heat flux at torch stagnation point

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Physics-based radiative model in TPS materials

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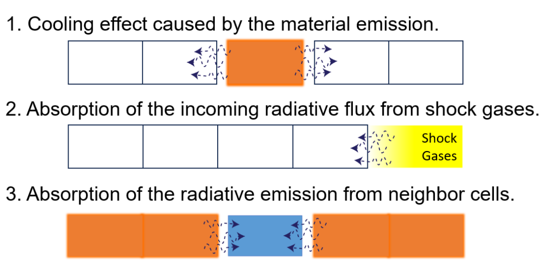
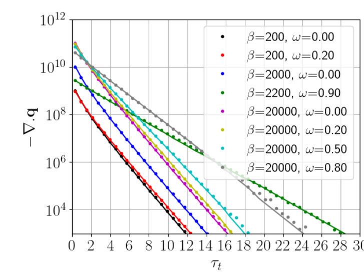
Abstract

Two modes of heat transfer within thermal protection systems (TPS) exist: conduction and radiation. The radiative heat transfer mode is caused by the radiative emission from highly non-equilibrium gases and by the radiative emission of high-temperature TPS material to itself. Solving the radiative transfer (RTE) equation is necessary for predicting in-depth heating and material response; however, high-fidelity numerical simulations are prohibitively expensive when accounting for the entire radiative spectrum. To address this challenge, a physics-based radiative model has been developed to solve the radiative heat transfer problem in an anisotropic scattering, absorbing, and emitting medium while maintaining minimal computational cost, enabling analysis across the entire radiative spectrum. The model framework assumes an infinite parallel-plates geometry. It divides the radiative source term of each control volume into three components: radiative cooling, absorption of external incident radiation, and the the self-emission of the material. The three components are calculated using two new radiative models: the exponential decay (ED) model [1] and the exponential weighted effective temperature (EWET) emission model [2]. The ED model calculates the radiative source term for a cold, anisotropic-scattering, absorbing medium subjected to external radiation. Meanwhile, the EWET emission model calculates the radiative emission of non-isothermal material with anisotropic scattering. The ED and EWET models have been verified against reverse Monte Carlo ray-tracing (RMCRT) solutions at different radiative properties. The proposed radiative model provides a reliable and computationally efficient solution for analyzing a radiative system that can encompass an infinite parallel plate.

Keywords: radiative model, EWET emission model, ED model, TPS, RMCRT, RTE



(a)



(b)

Figure 1: (a) Three-term radiative model illustration. (b) Exponential decay (ED) model verification.

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Fluidic nose tip for shape stability of hypersonic vehicles

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Abstract

A critical problem that arises at hypersonic speeds is the large aerodynamic heat fluxes that occur on hypersonic vehicles [1]. These heat fluxes and the resulting heat loads are detrimental to the structure and performance of these vehicles. They can also cause leading-edge nose blunting. This blunting negatively affects the hypersonic vehicle by changing the aerodynamic stability over the flight duration. This study looks at the possibility of using transpiration cooling as a method of protecting the shape of a sharp nose tip. Transpiration cooling is a three-fold active thermal protection system, cooling the vehicle through convective heat transfer, insulating the top surface of the vehicle to prevent overheating, and reducing oxidation at the surface which could increase radiative cooling [2, 3]. In addition, transpiration cooling has the potential to prevent blunting of the sharp nose tip by generating a protective layer acting as a fluidic nose as shown in Fig. 1. Although the fluidic nose tip would effectively generate a finite nose radius, full protection against ablation would mean that the finite nose radius remains constant over the flight duration and thereby offer shape stability. This study uses analytical models and correlations to examine the heat transfer on a sharp nose cone of a hypersonic vehicle with and without transpiration cooling. The study models two conditions at Mach 10, one at high altitude (18 km) and one at low altitude (1 km). This study will aid future work in testing the aerodynamic effects of transpiration cooling (i.e., concentration, boundary-layer effects, etc.) in the Actively Controlled Expansion Tunnel at Texas A&M University, and then testing in high enthalpy tunnels to determine the effectiveness of transpiration cooling for protecting sharp nose tips.

Keywords: Transpiration cooling, thermal protection systems, porous materials, shape stability, sharp nose tip

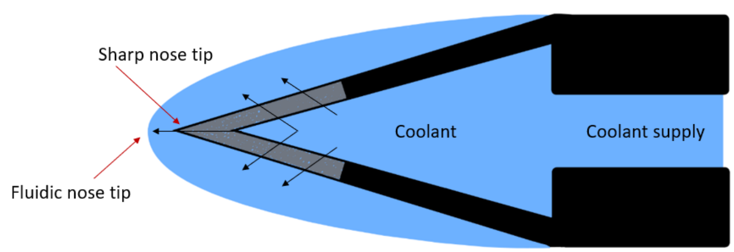

Figure 1: Transpiration cooled sharp nose cone (not to scale).

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Attempted Characterization of Arrhenius Parameters and Implementation to the Material Response Solver

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Abstract

The decomposition of solid species is modeled using a modified Arrhenius rate equation. The rate constants are determined by curve-fitting the equations to the thermogravimetric analysis (TGA) data. However, the rates can be adjusted according to the heating rates. These adjustments create challenges for material response simulations; therefore, efforts were made to establish correlations between heating rates and Arrhenius rate constants. The central assumption for this attempt is that the order of reaction is assumed to be 3 for all. The TGA data for phenolic resin were taken from the study by Guiles et al. [1]. A Python code was developed for the curve fitting process, which follows the work of Coheur et al.[2], and the resulting parameters can be seen in Fig. 1 (a) and (b) for solid density and density rates. The curve fitting was successful for seven reaction models; however, no trends were found in the Arrhenius parameters. Therefore, an interpolation method was introduced to estimate the Arrhenius parameters as a function of heating rate.

$$logA, 1/s = \begin{cases} 7.40277 \text{ if } \frac{\partial T}{\partial t} \leq 1 \\ 7.5645 \text{ if } 1 < \frac{\partial T}{\partial t} \leq 3 \\ 6.5500 \text{ if } 3 < \frac{\partial T}{\partial t} \leq 6 \\ 7.9624 \text{ if } 6 < \frac{\partial T}{\partial t} \leq 12 \\ 6.9055 \text{ if } 12 < \frac{\partial T}{\partial t} \end{cases} \quad (1)$$

$$\epsilon, kJ/kg.K = \begin{cases} 62.1918 \text{ if } \frac{\partial T}{\partial t} \leq 1 \\ 85.8674 \text{ if } 1 < \frac{\partial T}{\partial t} \leq 3 \\ 82.6924 \text{ if } 3 < \frac{\partial T}{\partial t} \leq 6 \\ 84.2792 \text{ if } 6 < \frac{\partial T}{\partial t} \leq 12 \\ 58.8703 \text{ if } 12 < \frac{\partial T}{\partial t} \end{cases} \quad (2)$$

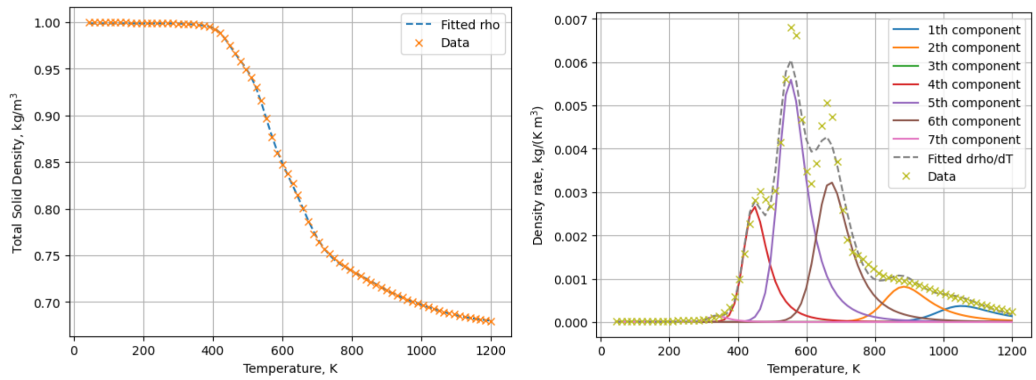
The equations 1 and 2 are the resulting pre-exponential constant and activation energy results for the 1st components of all heating rates.

The multi-pyrolysis species calculation was implemented in the KATS-MR solver. To test the new method, the 3 C/s heating rate was selected. The resulting components are shown in Fig. 2, and it can be seen that they are very close to the curve-fitting results seen in Fig. 1 (b).

Table 1: Gas reactions.

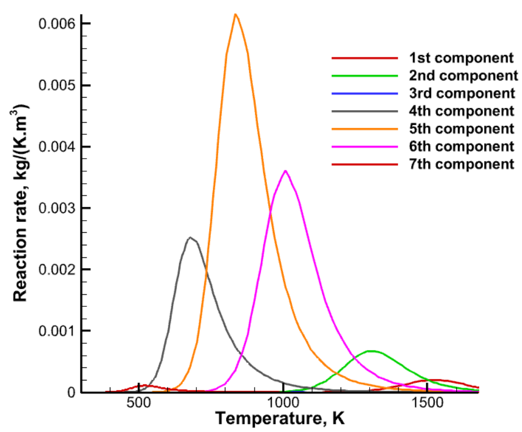
Reaction ID	1	2	3	4	5	6	7
H2	0.9640	0.9983	0.3334	0.0000	0.2695	0.9510	0.0000
CH4	0.0000	0.0000	0.3332	0.0000	0.2005	0.0264	0.0000
H2O	0.0000	0.0000	0.0000	0.6917	0.2451	0.0000	0.0004
CO	0.0298	0.0000	0.3330	0.0000	0.1098	0.0217	0.0000
CO2	0.0016	0.0001	0.0000	0.0062	0.0000	0.0000	0.0000
1-propanol, C3H8O	0.0004	0.0004	0.0001	0.0004	0.0004	0.0003	0.0074
2-propanol, C3H8O	0.0006	0.0001	0.0000	0.0741	0.0000	0.0000	0.9913
benzene, C6H6	0.0005	0.0001	0.0000	0.0000	0.0050	0.0000	0.0000
tolune,C6H5CH3	0.0004	0.0000	0.0000	0.0000	0.0086	0.0000	0.0000
phenol,C6H6O	0.0000	0.0000	0.0000	0.1265	0.0871	0.0000	0.0000
xylene,C8H10	0.0005	0.0001	0.0000	0.0000	0.0045	0.0000	0.0000
cresol,C7H8O	0.0000	0.0000	0.0000	0.0828	0.0512	0.0000	0.0000
dimethyl phenol,C8H10O	0.0010	0.0000	0.0000	0.0238	0.0116	0.0000	0.0000
trimethyl phenol, (CH3)3C6H2OH	0.0007	0.0004	0.0001	0.0003	0.0003	0.0003	0.0005
diphenyl ether,C12H10O	0.0005	0.0004	0.0001	0.0003	0.0004	0.0003	0.0004

Keywords: Solid decomposition, Arrhenius rates, multi-species pyrolysis gases



(a) Total solid density.
(b) Density rates.

Figure 1: Resulting curve fitting for 3 C/s case.



(a) Pre-exponential factor.

Figure 2: Reaction rate components with respect to temperature from KATS-MR simulation.

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Pyrolysis Mechanisms of Phenolic Resin in Cured SC-1008, PICA-D, and 3MDCP-IL

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Abstract

To obtain a better understanding of the thermal decomposition mechanisms of phenolic resin in carbon-phenolic composites and subsequently provide a foundation to develop improved materials response models for ablative heat shields, high-fidelity molar and mass yields of gaseous pyrolysis products from three phenolic materials have been obtained as a function of sample temperature (room temp – 1200 °C) and temperature gradient (1, 3, 6, 12, and 25 °C s^{-1}) using a molecular beam mass spectrometry technique. The three main materials studied are PICA-D (with chopped carbon fibers derived from lyocell), 3MDCP-insulation layer (with woven carbon fibers derived from polyacrylonitrile (PAN)), and cured SC-1008 phenolic resin, which is contained in both composites. A fourth material, PICA (with chopped carbon fibers derived from rayon), was studied at the temperature gradient of 6 °C s^{-1} for comparison with PICA-D. From the temperature-dependent molar yields, (example **Figure 1**), it is clear that the decomposition mechanisms across all materials are similar, however, the quantitative molar yields for cured SC-1008 phenolic resin compared to those of the carbon-phenolic composites are different. Five regions of decomposition can be clearly identified for cured phenolic resin, and these regions have been applied to the temperature-dependent yields for the carbon-phenolic composites to infer their decomposition mechanisms and identify differences from the cured resin. These differences have been investigated and identified as being a result of reactions between the resin and carbon fibers, density difference, curing procedures, from what polymer the carbon fibers where derived, and source of phenolic resin. A few of these differences between the decomposition of cured resin and carbon-phenolic composites include; introduction of condensation reactions that can happen between the phenolic resin and carbon fibers leading to decreased relative yield of volatile aromatics (such as phenol), possible products from the pyrolysis of the carbon fibers (such as N_2 from PAN in 3MDCP-IL), and reduced density and increased thermal conductivity of the composites resulting in the observation of very little change in the temperature dependent yields with increasing temperature gradient.

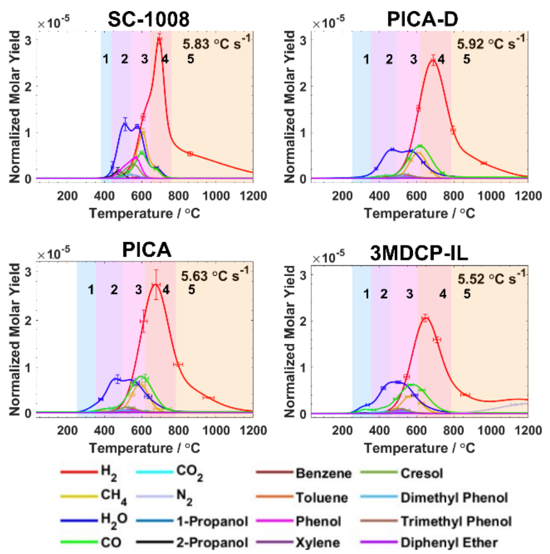

***Figure 1**. Examples of molar yields, normalized with respect to the total molar loss of the 16 dominant gaseous pyrolysis products for cured SC-1008, PICA-D, PICA, and 3MDCP-IL, with a temperature gradient of ~6 °C s^{-1}.*

Keywords: Phenolic resin, carbon fibers, carbon-phenolic ablator, pyrolysis, molar yields, mass yields.

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Molecular Beam Studies of the Oxidation of Vitreous Carbon and Isostatically Molded Graphite at High Temperatures

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Abstract

A detailed understanding of how carbon oxidizes under high-temperature conditions is essential for designing reliable thermal protection systems for hypersonic flight. We have studied the gas–surface reactions of hyperthermal atomic oxygen on two representative carbon materials: glassy carbon (vitreous carbon) and graphitic carbon (isostatically molded graphite). These molecular beam–surface scattering experiments were performed using a pulsed hyperthermal O-atom beam produced by a laser-detonation source. Both reactive and nonreactive efficiencies of the gas–surface interactions were quantified as a function of surface temperature. Product angular distributions and energy transfer results provided additional insight into the thermal and nonthermal mechanisms governing the gas–surface interactions. Previous molecular beam experiments [1,2] on the oxidation of hot carbon surfaces revealed long-residence-time thermal products (~0.2–10 ms) that had not been properly accounted for. New analyses now enable accurate quantification of these slow thermal desorption fluxes. Reaction efficiencies for all pathways that O atoms can take after striking the surface are shown in Figure 1. We have also investigated the temperature-dependent ablation behavior of vitreous carbon and isostatically molded graphite using the "table-top shock tunnel" (TTST) system. Comparative analyses between the molecular beam and TTST results suggest that differences in incident O-atom flux and surface oxygen coverage may lead to the observed variations in behavior. Ultimately, insights from both methods will contribute to the refinement of the Air–Carbon Ablation (ACA) model for future predictive applications.

Keywords: carbon oxidation, gas–surface interactions, ablation mechanisms, hyperthermal atomic oxygen

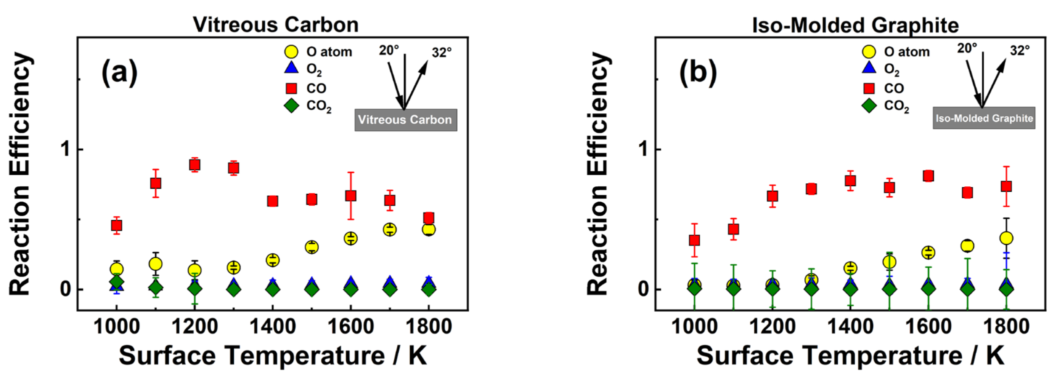

Figure 1. Reaction efficiencies of O, O_2, CO, CO_2 as a function of surface temperature following bombardment of the vitreous carbon (a) and isostatically molded graphite (b) with the atomic oxygen beam.

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Nano-scale characterization of thermal protection system materials using destructive techniques and deep learning models

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Abstract

In this study, 3D focused ion beam scanning electron microscopy (FIB-SEM) and deep learning-based segmentation techniques are combined to quantify and reconstruct the nanoporous structure of phenolic impregnated carbon ablator (PICA). The 3D FIB-SEM technique (Fig. 1A) enables high-resolution imaging of material microstructure by sequentially milling and imaging cross-sections with nanometer precision. Using the Helios NanoLab 660 dual-beam system at the University of Kentucky, 300 consecutive slices were captured with a cross-sectioning distance of 20 nm and a resolution of $4.27 \times 4.27 \times 20$ nm^3 (Fig. 1B), resulting in a 3D volume of $8.87 \times 5.29 \times 1.20$ μm^3. The entire acquisition took over 20 hours. Manual segmentation of each cross-sections is impractical and prone to bias; therefore, a 3D U-Net convolutional neural network was developed to automate segmentation. The model was trained using 2D labeled slices across three orthogonal planes (xy, xz, yz), eliminating the need to densely segment the entire volume for maintaining predictive accuracy. A weighted softmax loss function was employed, with unlabeled voxels excluded from the model learning. The final model was trained with an input size of $64 \times 256 \times 256$ voxels, 32 initial filters, 6 layers of depth, 100 epochs, and 100 augmented tiles, achieving a mean intersection-over-union (IoU) of 0.74. The segmentation results enabled reconstruction of a 3D volume that clearly distinguishes resin, fiber, and pore spaces as seen in Fig. 1C. Preliminary results highlight the complex multi-scale features of resin porosity and its attachment to carbon fibers. This integrated approach demonstrates that combining FIB-SEM imaging with deep learning-based segmentation provides a robust pipeline for nano-scale characterization of porous heat-shield materials. The framework not only reduces manual effort but also enhances reproducibility and scalability, paving the way for future studies on the relationship between microstructural porosity and the macroscopic performance of ablative composites.

Keywords: FIB-SEM, Nano-scale, PICA, Phenolic Resin

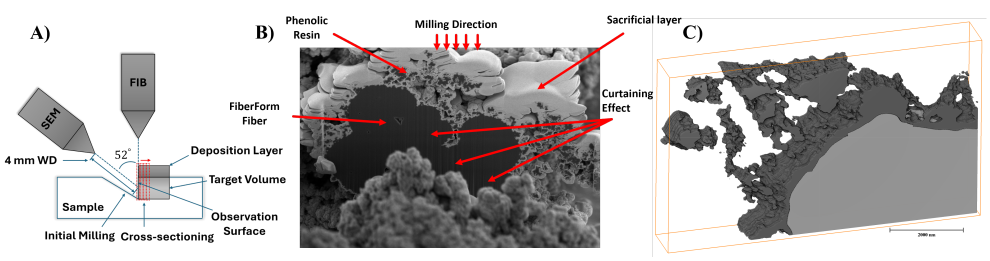

Figure 1: A) FIB-SEM setup, B) SEM image after milling, and C) Reconstructed 3D volume render from the U-Net prediction with a 0.74 mean IoU where dark grey is resin and light grey is fiber.

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Modeling and validation of radiative properties of porous composites

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Abstract

The entry velocity of space vehicles into different planetary atmospheres gives rise to different thermochemical phenomena. Heat shields that are used on space capsules are porous composite materials primarily constructed using carbon or silica-based fibers or weaves. These highly porous composite materials mitigate the convective and radiative components of heat flux through various processes, including oxidation, thermal decomposition, and pyrolysis. Radiative heating of heat shield materials is not a surface phenomenon, as electromagnetic radiation can penetrate into the material. To understand in-depth radiative heating, the optical properties of the material need to be computed. A computational model based on the Monte Carlo method has been developed to compute the optical properties of heat shields. The solver is referred to as Sparta-rMC. Following the development of the solver, an experiment has been designed to compute the transmission and backscattering of light. In this work, we present the verification and validation of the radiation solver Sparta-rMC by comparing it with transmission and backscattering data obtained from experiments. Apart from direct comparison with experiment data, additional parametric studies have been conducted to understand the parameters that affect changes in optical properties. Finally, the optical coefficients are computed for LI-2200 and FiberForm, along with the asymmetry factor.

Keywords: Radiative coefficients, porous ablator, x-ray computed tomography (XRCT), Monte Carlo radiation.

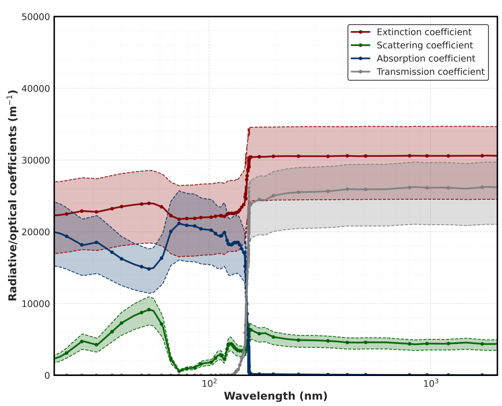

Figure 1: Radiative properties of LI-2200.

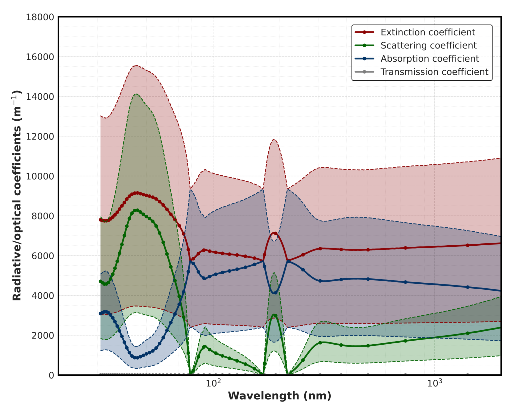

Figure 2: Radiative properties of FiberForm.

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Efficient parallel generation of extracted volume and material properties using the HERMES tool

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Abstract

Heterogeneous Effective Representative Multi-scale property Extraction Software (HERMES) is an integrated software tool designed to facilitate the extraction of microstructural information from X-ray computed tomography (XRCT) data, enabling the computation of material properties for advanced material analysis. The workflow begins with material segmentation, where a range of thresholding techniques are applied to classify each voxel as either material or void. These segmented volumes are then used to generate smaller sub-volumes through uniform random or deterministic sampling methods, and surface meshes are created using the marching cubes algorithm. These meshes are further processed and smoothed using either Laplacian filtering or screened Poisson surface reconstruction to enhance surface quality. Following mesh generation, a series of repair operations ensure the geometric integrity of the models, addressing common mesh defects such as non-manifold surfaces and duplicate vertices. The resulting meshes are used to compute key geometric properties, including closed volume, porosity, surface area, fiber diameter, and pore size distributions. Additionally, novel algorithms are employed to identify individual fibers, calculate their length, and determine their angle distributions by analyzing the fiber centerlines. The implementation of these methods allows HERMES to be a robust and flexible platform for analyzing the structure and properties of complex materials, enabling significant insights into material behavior at the microstructural level.

Keywords: Fiber identification, angle and pore size detection, x-ray computed tomography (XRCT),

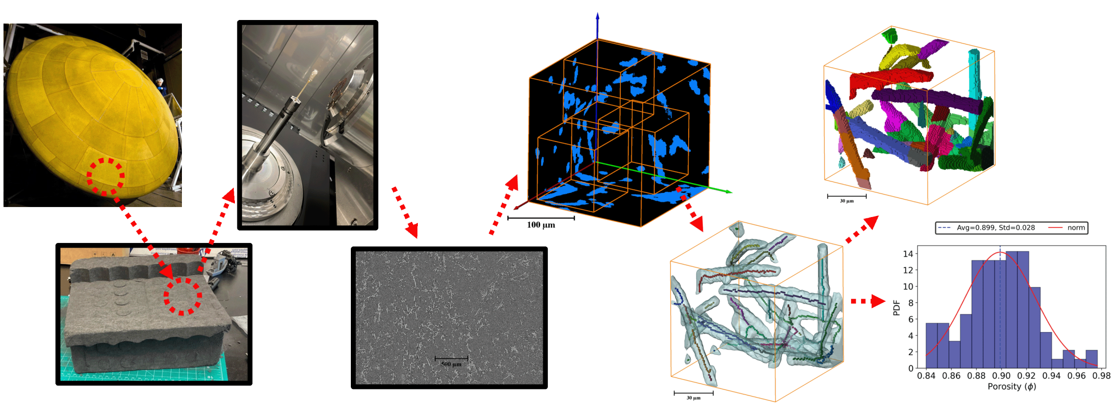

Figure 1: Schematic workflow of HERMES.

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The numerical study of effect of structural mechanics on thermal response of ablating material using fluid-material-structural coupled framework

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Abstract

We developed a fully coupled multi-physics simulation framework for high-fidelity modeling of TPS ablation, integrating fluid, thermal, structural, and chemical response solvers within a unified environment. The thermal and structural solvers share a common computational grid, enabling consistent evaluation of temperature-induced displacement, stress, and strain, while capturing thermal expansion, shear force, and internal pressure effects within the ablator. The framework implements a material constitutive model for both isotropic and orthotropic materials, with material variability incorporated to quantify uncertainty in response. The coupling sequence is initialized by the US3D flow solver, followed by the KATS thermal response solver and a structural mechanics module for detailed material analysis. The thermal response solver updates the aerothermal characteristics of the material and refreshes the fluid boundary conditions at each coupling interval. The flow solver then reconverges to steady state, and if convergence is not achieved, the coupling transitions into an implicit iteration to recompute the thermal response within the same interval.

Keywords: Coupling

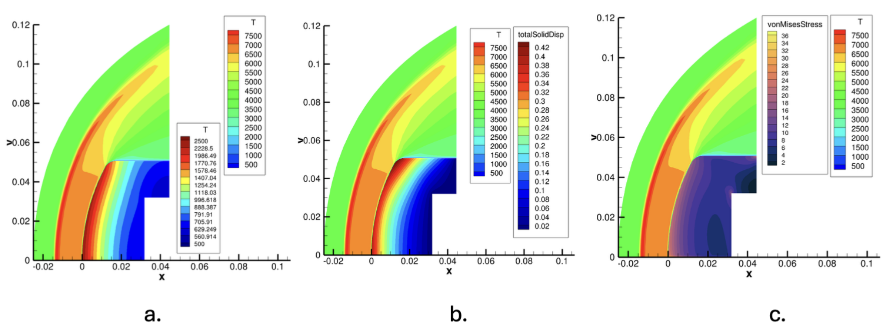

Figure 1: The US3D-KATS-SM coupling simulation of IsQ test case. (a) The fluid flow temperature and material temperature. (b) The total thermal stress acting on the material under the thermodynamic loads. (c) The analysis of von-misses stress inside the material under the thermodynamic loads.

References

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Assessment of Accessible Precursor Solutions for Thermal Protection Systems Fabricated using Additive Manufacturing Technique.

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Abstract

Most direct-ink-writing (DIW) formulations for thermal protection systems (TPS) are proprietary, expensive, or rely on reactive precursors that are unsafe for student research environments. This limits academic participation in additive-manufactured TPS material development. This work aims to establish a safe, low-cost, open, and reproducible silicone-based ink for DIW that can serve as an accessible research platform for TPS-relevant material studies. The ink was formulated from commercially available components vinyl-terminated PDMS, trimethylsilyl-terminated PMHS, fumed silica, and a low-ppm Karstedt's catalyst. The combination yields a controllable shear-thinning rheology suitable for DIW and cures under moderate staged heating to produce cohesive, elastomeric structures with strong interlayer adhesion. All mixing and curing steps were performed under standard fume-hood conditions using only benign siloxane chemistry, avoiding the handling risks associated with pyrophoric silazanes. The cured elastomers displayed firm, spring-like resilience, consistent layer cohesion, and shape retention through the staged-heat cure. Printing and processing reproducibility were verified with multiple batches prepared entirely from off-the-shelf materials. The approach provides a stable, low-hazard pathway for DIW research in standard laboratory settings. This open formulation provides a safe and transparent alternative to proprietary or hazardous DIW systems, lowering the barrier to entry for academic TPS research. Future work will implement multi-stage thermal processing of the printed elastomers: inert-atmosphere pyrolysis to convert the crosslinked siloxane network into a silicon-oxycarbide (SiOC) matrix; and incorporation of up to 30 wt% zirconium diboride (ZrB_2). These efforts will establish a reproducible pathway from silicone-derived polymers to refractory-filled ceramic composites relevant to TPS applications, while maintaining the project's commitment to open-science documentation and safe, educationally accessible additive manufacturing.

Keywords: hypersonics, additive manufacturing, material science

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Overview of the Kentucky Reentry Universal Payload System (KRUPS) project

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Abstract

The Kentucky Re-entry Universal Payload System (KRUPS) represents a university-driven, low-cost platform to experimentally investigate hypersonic re-entry physics, material response, and system survivability in flight. Conceived in 2013 as a senior design project, KRUPS has evolved into a modular experimental flight system. The KRUPS flight program has achieved a series of major milestones through its ongoing KREPE (KRUPS Re-entry Payload Experiment) campaigns. The KREPE-1 mission, launched aboard Northrop Grumman's NG-16 vehicle in November 2021, demonstrated the first successful university-led orbital re-entry of a hypersonic vehicle. Three capsules, two with Li-2200 TPS materials and one with a 3D-printed TPS, were ejected from the International Space Station (ISS). The capsules transmitted data during atmospheric re-entry, marking the first successful re-entry mission and collection of hypersonic flight data from a university-led platform. Building on these results, the KREPE-2 mission expanded the focus toward and additional sensors. Each capsule contained six thermocouples embedded within three precision-machined TC plugs, enabling orientation tracking and detailed temperature mapping during entry. Pressure ports at the stagnation and shoulder regions capture both total and differential pressures, facilitating trajectory reconstruction and estimation of angle-of-attack and sideslip. A mini-spectrometer, coupled via optical fiber to the stagnation line, records broadband (340–850 nm) emission spectra of the shock layer.

KRUPS demonstrates that small-scale, cost-effective flight experiments can substantially accelerate validation of hypersonic models and TPS materials. The modular architecture establishes a scalable testbed for future distributed re-entry research. By integrating computational modeling, additive manufacturing, and in-situ diagnostics within a flight-qualified system, KRUPS provides an enduring platform to advance predictive simulation, material innovation, and workforce training in the emerging hypersonic ecosystem.

Keywords: Hypersonic flight platform, Thermal protection system testing, In-flight diagnostics

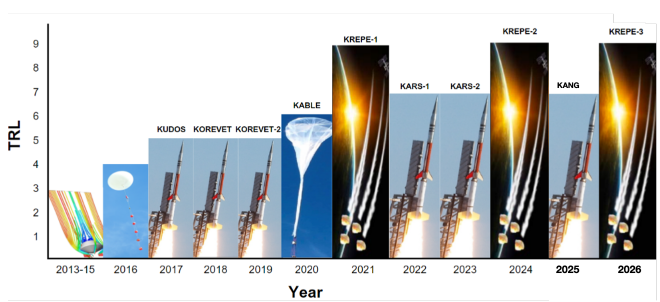

Figure 1: The KRUPS project over the years.

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Ablators modeling: Past, Present and Future

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A brief review of the evolution of material response models for thermal protection systems (TPS) is presented. Starting from simple concepts, material response models have evolved into multidisciplinary models that couple heat transfer, fluid mechanics, pyrolysis and chemistry. An example of current challenges in understanding material response to atmospheric entry is discussed showing the importance of high-fidelity modeling in providing clarity into off-design material response. These recent challenges have pushed multidisciplinary models to include coupling formulations to solid mechanics response. The Volume Averaging Method (VAM) is reviewed briefly from its basic derivation, to show the terms that couple the averaged governing equations to the solid mechanics equations. We show that when VAM is applied to particle methods, we recover the Smooth Particle Hydrodynamics (SPH) formulation plus a rigorous treatment of the boundary conditions. In the near-future, investments in current hyperscale computer centers will accelerate the possibility of reaching a digital twin for material response of ablative materials during atmospheric entry. It is anticipated that particle methods will be the scalable methods of choice to run on hyperscale clusters.

Aerospace Activities at the New Mexico State University (NMSU)

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Abstract

This presentation describes the engineering and scientific contributions, by the MAE faculty, to the aerospace community over that past five years. Only NMSU offers the BS, MS, ME and Ph.D. aerospace engineering degrees in the State of New Mexico. The aerospace program identifies itself as a southwest USA leader in several research areas based on research publications, research funding and connectivity to industry. In particular, the aerospace faculty are actively engaged in research that supports hypersonic flight for both national security and commercial purposes. NMSU is, at all levels, committed to this thrust area. Faculty and students from the MAE Department are making contributions in hypersonics using its present tunnel test and laser facilities and instrumentation while seeking a new multimode hypersonic wind tunnel. Further, the aerospace faculty are increasingly involved in investigating fundamental physics through CFD, characterizing and analyzing materials for thermal protection systems, investigating ablative processes in new materials, developing new heat flux sensors based on non-traditional materials and designs while developing novel data reduction methods. To close, a vision statement is presented on extending NMSU capabilities and involvement in hypersonics.

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Building an Experimental and Computational Framework for Ablative Thermal Protection Systems

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Abstract

The design of ablative Thermal Protection Systems (TPS) requires a thorough understanding of material behavior across multiple length scales. TPS materials exhibit complex, multi-scale responses, which makes it essential to link microstructural characteristics with macroscopic thermophysical and chemical properties.

In this work, we present the establishment of a new laboratory dedicated to characterizing and developing TPS materials for hypersonic applications at NMSU. The lab integrates a suite of experimental techniques, including microscopy and micro-computed tomography for microstructural analysis, Transient Plane Source (TPS) for thermal conductivity measurement, pycnometry, and TGA/DSC for thermal and compositional assessment. These methods are complemented by computational modeling to interpret and upscale material properties, enabling reliable characterization across scales.

Two custom experimental setups are currently being developed: one to study plasma-material interactions, following the approach of Anderson [1], and another laser-based system designed to investigate carbon deposition phenomena [2, 3]. In addition, we are exploring additive manufacturing as a pathway for tailoring and fabricating TPS components.

Future efforts will focus on consolidating these capabilities and extending the work toward new techniques, including species quantification and mechanical property evaluation, to further advance the understanding and design of ablative materials.

Keywords: ablation; carbon/phenolic; thermal protection system; multi-scale modeling

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Development of a Laser-Heated Facility to Investigate Coking in Ablators

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Abstract

Carbon composites protect spacecraft during atmospheric entry, but their performance is critically dependent on poorly understood gas-surface interactions (GSI). During entry, the pyrolysis gases percolate through the hot porous char and react through carbon deposition (coking), altering permeability, thermal conductivity and internal pressure, directly affecting the integrity of the TPS and aerothermal predictions [1, 2]. Conventional arc jets offer limited diagnostic access and short test durations, which hinders the fundamental characterization of GSI [3, 4].

In this work, we develop a laser-heated facility enabling controlled, long-duration studies under decoupled thermal and chemical conditions. The laser's non-contact, top-down heating physically decouples energy input from backside gas injection, isolating surface heating from gas transport. This enables independent study of competing thermal vs. chemical deposition mechanisms which is critical for validating finite-rate GSI models that current arc-jet data cannot provide. The laser delivers precisely controlled heat fluxes faster than furnaces, simulating transient entry events while minimizing secondary reactions. Temperature profiles and gradients are programmable and reproducible, which is essential for parametric model validation. Non-contact heating avoids optical interference from heating elements or plasma, enabling non-intrusive pyrometry, spectroscopy, and imaging during testing. Combined with vacuum operation and mass flow controlled gas injection, this yields a controlled chemical environment for isolating coking kinetics.

The facility (Fig. 1) uses a 1.5 kW continuous-wave laser to heat porous carbon samples in a vacuum chamber. Pyrolysis-representative gases (e.g., methane) are injected from the backside via mass flow controllers while pyrometry monitors surface temperature in real-time. Preliminary modeling confirms achievement of TPS-relevant temperatures (>1500 K), where methane deposits solid carbon, reducing permeability and increasing pressure buildup risks.

Post-test SEM and micro-CT will characterize deposition spatial distribution and pore evolution. By varying gas composition, temperature, and residence time under decoupled conditions, we will generate high-fidelity kinetic data to develop and validate predictive chemical models for next-generation TPS design.

Keywords: pyrolysis, thermal protection systems, gas-surface interactions

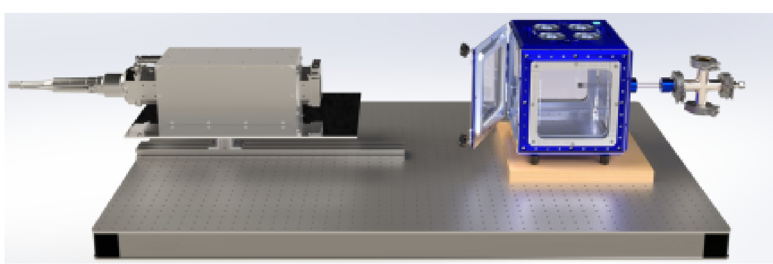

Figure 1: Facility schematic.

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