

16th Ablation Workshop

Sept 1–3, 2026

New Mexico State University
Corbett Center Student Union

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BOOK OF ABSTRACTS

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16th Ablation Workshop

Sept 1–3, 2026

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

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16th Ablation Workshop

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Monday

August 31, 2026

Welcome Cocktail Mixer and Registration**17:00 - 20:00** Stan Fulton Center

Tuesday

September 1, 2026

08:00 Registration and Breakfast**08:40** Welcome Remarks - MAE Dept. Head Dr. Frankel**Technical Session #1: Overviews and Applications** *Chair: Prof. Torres-Herrador***09:00** Overview Office Naval ResearchEric Marineau (*Office Naval Research*)**09:20** Overview from SNLScott Roberts (*Sandia National Laboratories*)**09:40** Dragonfly TPS ChallengesMichael Wright (*NASA Ames Research Center*) page 33**10:00** Qualification in CO₂ of the TPS and the aerothermal instrumentation for the EXOMARS RFM missionGregory Pinaud (*ArianeGroup SAS*) page 64**10:20** KRUPS: Overview of the KREPE-3 flights and beyondAlexandre Martin (*University of Kentucky*) page 98**10:40** Coffee Break**Technical Session #2: Experimental I** *Chair: Dr. Engerer***11:00** Multiscale Analysis of Ablators Tested on an Oxy-Acetylene Test BedSamantha R. Bernstein (*University of Texas - Austin*) page 15**11:20** Atomic oxygen measurements via coherent anti-Stokes Raman Scattering: a new path for study of recombination physicsSean Kearney (*University of Illinois Urbana-Champaign*) page 63**11:40** Investigations of High-Temperature Oxygen-Carbon Ablation by Molecular Beam-Surface ScatteringTimothy K. Minton (*University of Colorado Boulder*) page 74**12:00** Modeling and simulation of radiometer placement experiments in the NASA Ames mARC II arc jet facilityAndrea Scaboro (*University of Illinois Urbana-Champaign*) page 45**12:20** Lunch**Technical Session #3: Coupling** *Chair: Dr. Borner*

13:20	Staggered coupling of a high-order flow solver and a material solver for ablation in high-enthalpy flows	
	Julien Klauner (<i>UCLouvain, ULB, VKI</i>)	page 20
13:40	Influence of Surface Recession on Transitional Fluid–Ablation Interactions over a Mach 8 Compression Ramp	
	Kumaraguru Sethunarayanan (<i>University of Maryland, College Park</i>)	page 76
14:00	Multivelocity Formulation Discretized Using Combined Discontinuous Galerkin and Material Point Methods for Ablation Simulations	
	Duan Z. Zhang (<i>Los Alamos National Laboratory</i>)	page 75
14:20	Comparison of Fluid–Material Coupling Strategies for Hypersonic Ablation	
	Gabriel Merlaud (<i>University of Bordeaux</i>)	page 31
14:40	Analyzing the impact of GSI models on Fluid-Radiation Coupled Simulations	
	Alessandro Meini (<i>University of California, Irvine</i>)	page 67
15:00	Coffee Break	
Technical Session #4: Experimental II <i>Chair: Prof. del Val</i>		
15:20	ARCTRON: A Rapid Experimental Proving Ground for TPS Experiments and Arcjet Technology Development	
	Arnaud Borner (<i>Analytical Mechanics Associates, Inc. at NASA Ames Research Center</i>)	page 60
15:40	Kalman Filtering and RTS Smoothing for Arc-Jet Sample Edge Tracking	
	Alexandre Quintart (<i>Flying Squirrel</i>)	page 86
16:00	Development of Thermal Protection Systems Research Capabilities at NMSU	
	Francisco Torres-Herrador (<i>New Mexico State University</i>)	page 81
16:20	Mesoscale Test Cases Presentation	
	Francisco Torres-Herrador (<i>New Mexico State University</i>)	
	Savio J. Poovathingal (<i>University of Kentucky</i>)	
16:30	Poster Pitch	
17:00	Poster Session	
19:00	End of Poster session	

Wednesday

September 2, 2026

08:00 Breakfast

Technical Session #5: ML / UQ *Chair: Prof. Poovathingal*

- 08:40 Reduced-Order Modeling of a One-Dimensional Charring Ablator Using Coupled Thermal-Decomposition Dynamics**
 Brianna Morales (*University of California Merced*) page 56
- 09:00 Few-shot multistage phase classification in CT scans of carbon-carbon composites**
 Xiongjun Wu (*DEVCOM ARL*) page 71
- 09:20 Stochastic reconstruction of ablating material properties for uncertainty propagation in material response simulations**
 Joseph Schulz (*NASA Ames Research Center*) page 72
- 09:40 Uncertainty Aware Air Carbon Ablation Model From Molecular Beam Data**
 Graham John Larson (*University of Minnesota*) page 58
- 10:00 In-Situ micro-CT Analysis of RTV with Dispersed Phenolic Micro-Balloons**
 Spencer Dansereau (*University of Colorado Boulder*) page 94
- 10:20 Physics-Constrained Trajectory-Coupled Scientific Machine Learning for Accelerated End-to-End Hypersonic Entry Design**
 Rui Fu (*University of Kentucky*) page 99
- 10:40 Coffee Break**

Technical Session #6: Thermochemistry *Chair: Prof. Lachaud*

- 10:50 A Novel Thin-Layer Model for Finite Rate Ablation Closure**
 Dallin Lee Littlewood (*Sandia National Laboratories*) page 38
- 11:10 Sublimation of carbon materials**
 Savio J. Poovathingal (*University of Kentucky*) page 79
- 11:30 Reactive Coverage Model Fit to Graphite Oxidation Dataset Across Pressure Regimes**
 Nicholas Anderson (*University of Illinois at Urbana-Champaign*) page 97
- 11:50 High-throughput molecular dynamic simulation for char-yield prediction and materials screening**
 Md Razaul Karim (*The University of Texas at El Paso*) page 93
- 12:10 Thermal Conductivity Characterization of Commercial Carbon Fibers Up to 2700 °C**
 Yixin Luo (*CAER, University of Kentucky*) page 16
- 12:30 Lunch**

Technical Session #7: Thermomechanical *Chair: Mr. Bersbach*

- 13:30 Multiscale aero-thermo-chemo-mechanics modeling of Thermal Protection Systems in Σ MIT**

	Raul Radovitzky (<i>Massachusetts Institute of Technology</i>)	
13:50	Simulations of Yarn Micro-Mechanics of Woven Heat Shield Materials (3MDCP)	
	Elizabeth Suehr (<i>NASA NPP</i>)	page 23
14:10	Thermo-poro-mechanical modeling of RTV intumescence	
	Sreevishnu Oruganti (<i>Amentum Technology Inc. at NASA Johnson Space Center</i>)	page 43
14:30	Thermomechanical modeling of woven materials with particle-based, explicit-fiber simulations	
	Andrew P. Santos (<i>NASA Ames Research Center</i>)	page 41
14:50	An Iterative Coupling Methodology for Fully Coupled Pyrolysis, Gas–Surface Interaction, and Thermo-Structural Analysis	
	Bibin Joseph (<i>University of Kentucky</i>)	page 42
15:10	Coffee Break	
Technical Session #8: GSI Chair: Dr. Wu		
15:20	Investigations the influence of gas-surface reactions to compute RF Blackout in atmospheric entry	
	Alexandra Richet (<i>CEA</i>)	page 65
15:40	Development of a Modular Coupling Framework for Aerothermodynamic and Material Response Simulations	
	Raghava S. C. Davuluri (<i>Purdue University</i>)	page 90
16:00	Implicit coupling between free flow and pyrolyzing porous materials: from micro-CT-scale deformation to particle-scale interaction	
	Abderrahman M'jikou (<i>University of Bordeaux</i>)	page 29
16:20	A Computational Thermo-Chemo-Poro-Mechanical Model of Pyrolyzing Ablative Thermal Protection Systems	
	Christopher T Quinn (<i>Massachusetts Institute of Technology</i>)	page 53
16:40	Ice micrometeoroid ablation modeling on aeroshells	
	Erin Heilman (<i>Earth and Environmental Sciences Division, Los Alamos National Laboratory</i>)	
17:00	Discussing Ablation Test-Case #4	
	Jean Lachaud (<i>University of Bordeaux</i>)	page 96
18:00	Gala Dinner: Farm & Ranch Museum	

Thursday - ITAR Session**September 3, 2026****08:15** Breakfast**08:45** Visit PSL**09:30** Coffee Break**ITAR Session at PSL** *Chair: Prof. Martin***09:50** **Overview Office Naval Research**Eric Marineau (*Office Naval Research*)**10:10** **Characterization of the resin structure in PICA**Savio Poovathingal (*University of Kentucky*)page 77**10:30** **Aerothermal Modeling of 2.5DCC in H1 Arc Heater**Chuck Bersbach (*Raytheon-RTX*)page 36**10:50** **Aerothermal Evaluation of 2.5DCC in H1 Arc Heater**Chuck Bersbach (*Raytheon-RTX*)page 37**11:10** **Under Pressure: The Artemis I Heatshield Char Loss Investigation and Artemis II's Successful Entry**Joseph C. Ferguson (*NASA Ames Research Center*)page 48**12:00** Lunch**13:00** **Visit MAE Hypersonics lab****Thursday - Non-ITAR****September 3, 2026****08:15** Breakfast**08:45** **Visit MAE Hypersonics lab**

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Thibaud Coelho, Nell Trouillet, Alexandre Duméry, Audrey Duphil, Cécile Gaborieau, Alain Sommier, Olivier Ledain, Antonio Cosculluela, Jean Lachaud (*University of Bordeaux*)
- **An Experimental Method for Measuring Gas Diffusivity and Tortuosity in TPS Materials** page 22
Jack W. Wooten, Michael W. Renfro (*University of Kentucky*)
- **Aerothermal Assessment of Supersonic Flows Past a Roughened Sphere-Cone** page 24
Nikhil Kohar, Mostafa Aghaei-Jouybari (*The University of Kansas*)
- **Aerothermal Characteristics of Supersonic Channel Flows Over Sinusoidal Roughness** page 25
Adrian Cabildo Arias, Mostafa Aghaei-Jouybari (*University of Kansas - Lawrence*)
- **Developing Digitally Knitted Textile Architectures for Thermal Protection Systems** page 26
Jennifer Meakins, Ashley Grace Smith & Cayenne Warren (*University of Kentucky*)
- **The evolution of transport properties in charring carbon-phenolic ablators** page 28
Henry X. Varona, Erik Poloni, Gregory S. Elliott, Francesco Panerai (*University of Illinois Urbana-Champaign*)
- **Shock tube - plasma wind tunnel similarity based on optical emission spectroscopy** page 34
A. Fagnani, S.R. Latimer, B.A. Cruden, O. Chazot (*NASA Ames Research Center*)
- **Modeling volumetric oxidation and oxidation-induced mechanical degradation in porous graphite TPS** page 35
Akhil Ambardekar, Raul Radovitzky (*Massachusetts Institute of Technology*)
- **Probabilistic inference of air-carbon ablation model parameters using conditional flow matching** page 39
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- **Machine learning-accelerated embedded chemistry calculations for the simulation of oxidation transitions in silicon carbide TPS** page 47
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- **Spatially resolved emission spectroscopy around graphite samples in nitrogen/methane plasmas** page 49
Nimesh Chaulagain, Stefan Löhle, Savio Poovathingal, Alexandre Martin, Dan Fries (*University of*

Kentucky)

- **Dust Effects on the Aerothermal Environment and TPS Material Response during Martian Hypersonic Entry**page 51
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- **Modeling of a high velocity oxygen fuel (HVOF) torch**page 55
Joseph Chaplin, Gehr Fergusson, Kenneth Kane, Alexandre Martin (*University of Kentucky*)
- **A Computational Framework for Heterogeneous Oxidation and Fracture in Ultra-High Temperature Ceramics** page 57
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- **Oxygen-Carbon Reactions in FiberForm Investigated with Molecular Beam Mass Spectrometry**page 85
Henri N. Doucet, Celeste H. Guiles, Timothy K. Minton. (*University of Colorado-Boulder*)

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- **BEAST: Expanding Sustainable Data Infrastructure for High-Enthalpy Facilities** .page 88
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 - **Artificial Neural Network for Material and Dimensional Characterisation of Thermally Induced Distortion in Extruded Metals** page 100
Saisruthi Kotagiri, Venkata Sirimuvva Chirala (*New Mexico State University*)
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Bryce Richards, Andreas Gross, Fangjun Shu (*New Mexico State University*)
 - **Stability Analysis of Hypersonic Thermochemical Nonequilibrium Boundary Layer** page 108
Angel Zuniga Ramirez, Servio Tulio Haramura Bastos, Andreas Gross, Qiong Liu (*New Mexico State University*)
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Attendees

Name	Institution	Status
Mostafa Aghaeijouybari	<i>University of Kansas</i>	Assistant Professor
Arafat Ahmed	<i>New Mexico State University</i>	Graduate Research Assistant
Victoria Alfonso-Westphal	<i>New Mexico State University</i>	NMSGC Program Specialist
Renato Cruz Alvarez	<i>New Mexico State University</i>	Undergraduate student
Akhil Ambardekar	<i>Massachusetts Institute of Technology</i>	Graduate Student
Joshua Anders	<i>Holloman High Speed Test Track</i>	Mechanical Engineer
Nicholas Anderson	<i>University of Illinois at Urbana Champaign</i>	Graduate Research Assistant
Adrian Cabildo Arias	<i>University of Kansas</i>	Graduate Student
Servio Tulio Suenai Haramura Bastos	<i>New Mexico State University</i>	Research Assistant
Kyle Benalil	<i>Corvid Technologies</i>	ADVANCED WEAPONS SYSTEMS
Samantha Bernstein	<i>The University of Texas at Austin</i>	Graduate Research Assistant / PhD Candidate
Charles Bersbach	<i>Raytheon-RTX</i>	Senior Technical Fellow
Eric Blades	<i>ATA Engineering, Inc.</i>	Technical Fellow & Vice President
Matthew Blenis	<i>Wichita State University NIAR</i>	Senior Research Engineer - Advanced Materials Research
Nicole Block	<i>Holloman High Speed Test Track</i>	Mechanical Engineer
Henry Boesch	<i>University of Illinois at Urbana-Champaign</i>	Graduate Student
Arnaud Borner	<i>Analytical Mechanics Associates, Inc.</i>	Technical Area Lead, Thermal Protection Materials Branch
Tyler Brooks	<i>New Mexico State University</i>	Faculty
David Case	<i>New Mexico State University</i>	Undergraduate student
Luis Chacon	<i>Corvid Technologies</i>	Aerothermal Engineer
Joseph Chaplin	<i>University of Kentucky</i>	Research Assistant
Samuel Chen	<i>JHU/APL</i>	Senior Research Staff
Stanley Cheng	<i>New Mexico State University</i>	Staff
Venkata Sirimuvva Chirala	<i>New Mexico State University</i>	Faculty
Thibaud Coelho	<i>Université de Bordeaux</i>	Research intern
Karel Coetzee	<i>AWE</i>	Aerothermal
David Cornelius	<i>Analytical Mechanics Associates, Inc (AMA, Inc)</i>	Vice President/Program Manager
William Dai	<i>MIT</i>	Graduate Student
Spencer Dansereau	<i>University of Colorado</i>	Research Faculty
Raghava S. C. Davuluri	<i>Purdue University</i>	Postdoctoral Research Assistant
Henri Doucet	<i>University of Colorado Boulder</i>	PhD Student
Eduardo Chavira Durán	<i>New Mexico State University</i>	Undergraduate student
Robert Edmonds	<i>Los Alamos National Laboratory</i>	Scientist
Abraham Ellis	<i>Sandia National Laboratories</i>	Senior Manager, R&D Science and Engineering
Jeffrey Engerer	<i>Sandia National Laboratories</i>	Research Scientist & Engineer
Andrea Fagnani	<i>NASA Ames Research Center</i>	NASA Postdoctoral Fellow
Joseph Ferguson	<i>NASA Ames Research Center</i>	Orion TPS Deputy System Manager
Mariano Fernandez	<i>Liberty Fusion</i>	Business Development Manager
Jay Frankel	<i>New Mexico State University</i>	Faculty
Dan Fries	<i>University of Kentucky</i>	Faculty
Kazuhisa Fujita	<i>ElevationSpace Inc.</i>	CTO
Brandon Gama	<i>New Mexico State University</i>	PSL R&D Engineer
Andres Ibarra Gonzalez	<i>New Mexico State University</i>	Graduate student (MS or PhD)
Celeste Guiles	<i>CU Boulder</i>	Post. Doc
H. Berk Gur	<i>University of Kentucky</i>	Research Assistant
David Hash	<i>NASA</i>	SUPV RSCH AST, TECHNICAL MANAGEMENT
Justin Haskins	<i>Nasa</i>	Branch chief
Erin Heilman	<i>Los Alamos National Laboratory</i>	Scientist
Estela Heredia	<i>New Mexico State University</i>	NMSGC Staff
Francisco Torres Herrador	<i>New Mexico State University</i>	Faculty
Zackery Holguin	<i>Holloman High Speed Test Track</i>	Mechanical Engineer
Hubert H. Quintana III	<i>New Mexico State University</i>	Undergraduate student
David Jauregui	<i>New Mexico State University</i>	Faculty
John Jessen	<i>Holloman High speed Test Track</i>	Engineering Deputy Flight Chief
Brendan Jones	<i>Lawrence Livermore National Laboratory</i>	High Temperature Materials Analyst

Name	Institution	Status
Justin Jones	Toyon Research Corporation	Analyst
Bibin Joseph	University of Kentucky	Graduate research assistant
Clayton C Mason Jr	New Mexico State University	Faculty
William Stellwag Jr	LANL	Engineer
Md Razaul Karim	The University of Texas at El Paso	Graduate Research Assistant
Sean Kearney	University of Illinois Urbana-Champaign	Professor
Robert Keene	Sandia National Labs	Manager of Thermal Testing, NSTTF
Claire Kent	University of Colorado at Boulder	Graduate research assistant
Julien Klauner	Catholic university of louvain	PhD Student
Jessica Klusmeyer	New Mexico State University	Graduate Student
Devin Knotts	New Mexico Tech	EFDL Graduate Research Assistant
Nikhil Kohar	The University of Kansas	Graduate Research Assistant
Steven Kooi	MIT	Principal Research Scientist
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Dallin Littlewood	University of Utah	Graduate Intern
Joachim Lohn-Jaramillo	Spaceport America	Aerospace Engineer
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Eric Marineau	Office of Naval Research	Program Officer
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Isaac Nelson	Sandia National Laboratories	R&D Mechanical Engineer
Zachary Nieto	New Mexico State University	Graduate student (MS or PhD)
Michael Nucci	ATA Engineering	Technical Director, Multiphysics
Brandon Oliver	NASA - Johnson Space Center	Orion Aerothermodynamics/TPS
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Adrian Perez	New Mexico State University	Undergraduate student
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Finn Pias	New Mexico State University	MAE Communications Student Assistant
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Jeff Pietryga	Los Alamos National Lab	Los Alamos National Lab
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Christopher Quinn	Massachusetts Institute of Technology	PhD Candidate
Alexandre Quintart	Flying Squirrel	Aerospace Engineer
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Bryce Richards	Bryce Richards	Graduate Research Assistant

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Multiscale Analysis of Ablators Tested on an Oxy-Acetylene Test Bed

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Abstract

A multiscale modeling methodology was developed to analyze the behavior of Phenolic Impregnated Carbon Ablator (PICA) and novel quartz with powdered polysiloxane resin (Q/pUHTR) being tested on an Oxy-Acetylene Test Bed (OTB) with advanced diagnostics. Microstructure scans of PICA were taken at the Lawrence Berkeley National Laboratory (LBNL) Advanced Light Source (ALS). Scans were taken at a resolution of 0.649 microns per pixel on the x-ray synchrotron. Using machine learning segmentation, the material was segmented into three phases: fiber, resin, and void (air). The segmented microstructure was then used to create a mesh using Sandia's Krino software. This mesh was then used to calculate the mesoscale material properties. The thermal conductivity, specific heat, porosity, and density for each PICA sample were calculated using Sandia's Sierra/Aria program. The surface thermochemistry for each sample was calculated using ACE and previously measured properties for the OTB's environmental chemistry. The kinetic modeling parameters were estimated using the Kissinger method and TGA testing reported in literature. The surface thermochemistry, kinetic modeling parameters, and macroscale material properties calculated using the mesh of material microstructures and individual component material properties were then input into the Sandia's Aria material response model. A 3D sample geometry was generated using Sandia's Cubit program to match the actual tested sample dimensions. A three-way comparison was undertaken between a material response model using traditional PICA values from experimental data and literature, a material response model generated using bulk mesoscale material properties generated from microstructures, and the experimental data. Specifically, the recession, surface temperature, and in-depth temperatures were compared between the model predictions and OTB experimental data. If there is time, this same analysis will also be performed using the University of Kentucky's KATS material response program and the test environment will expand to include data from the Stardust Sample Return Capsule in addition to the OTB. In the future, this MR model will be used to facilitate the design of novel TPS materials that are optimized for specific test or mission conditions. This will be done by inverting the methodology outlined above to input ablative performance and output optimized material microstructures.

Keywords: ablation, thermal protection systems, micro-CT, segmentation, material response modeling

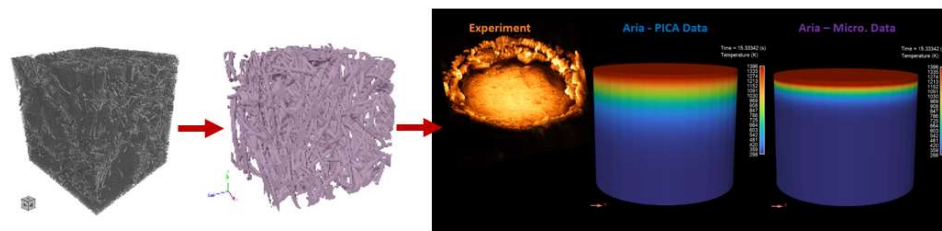


Figure 1: Micro-CT Render, 3D Mesh, Experimental Video, and Macroscale Material Response

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Thermal Conductivity Characterization of Commercial Carbon Fibers Up to 2700 °C

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Abstract

Direct measurement of the thermal conductivity of carbon fibers at elevated temperatures has long been desired because carbon-fiber-reinforced polymer (CFRP) and carbon/carbon (C/C) composite materials are widely used in aerospace, automotive braking systems, defense applications, and other engineering fields that often require operation at high temperatures, in some cases up to 2700 °C [1] or higher. As the primary constituent of these composites, carbon fibers play a critical role in governing their thermal performance. While thermal conductivity measurements of composite materials are relatively accessible, direct characterization of carbon fibers with no matrix at elevated temperatures remains challenging. Previous studies have attempted to estimate thermal conductivity through correlations with electrical conductivity [2], Raman spectroscopy techniques [3], and 3 ω method [4]; however, these approaches are indirect and are not readily applicable at high temperatures.

In this work, the thermal conductivity of two commercial carbon fibers (PAN-based T300 and mesophase pitch-based Dialead K13916) was determined using the relationship $k = \alpha \rho C_p$, where thermal diffusivity (α) was measured by Laser Flash Analysis (LFA), density (ρ) was calculated from the coefficient of thermal expansion (CTE) which was obtained using dilatometry, and heat capacity (C_p) was measured by simultaneous thermal analysis (STA). The objective was to provide critical thermophysical property data up to 2700 °C for modeling, simulation, and design of carbon-fiber-based composite materials. Among these measurements, thermal diffusivity characterization by LFA presents a unique challenge because collimated fiber bundle specimens must be aligned and constrained with minimal contact to the LFA sample holder while maintaining structural integrity. Furthermore, no binders or support materials can be used, as they may interfere with heat transfer during testing. To address these challenges, two specimen-preparation methods were developed to produce straight, well-collimated fiber bundles for PAN-based and pitch-based carbon fibers, enabling reliable thermal diffusivity measurements (Figure 1).

The phase 1 results (up to 1000 °C) demonstrate that the room-temperature thermal conductivities of PAN-based T300 carbon fiber and pitch-based K13916 carbon fiber are in good agreement with manufacturer-reported values (Figure 2). For T300 carbon fiber, thermal conductivity increases with temperature, primarily due to increases in heat capacity and density, while thermal diffusivity remains relatively constant. In contrast, K13916 carbon fiber exhibits overall much higher in thermal conductivity but a slight decrease with increasing temperature, driven mainly by a significant reduction in thermal diffusivity, which outweighs the modest increase in heat capacity and slight decrease in density (Figure 3). These findings and methods provide solid foundation for future phase 2 (up to 2700 °C) measurements for advanced composite material applications and thermal performance modeling.

Keywords: thermal conductivity, 2700 °C, carbon fiber, LFA, Dilatometer, STA

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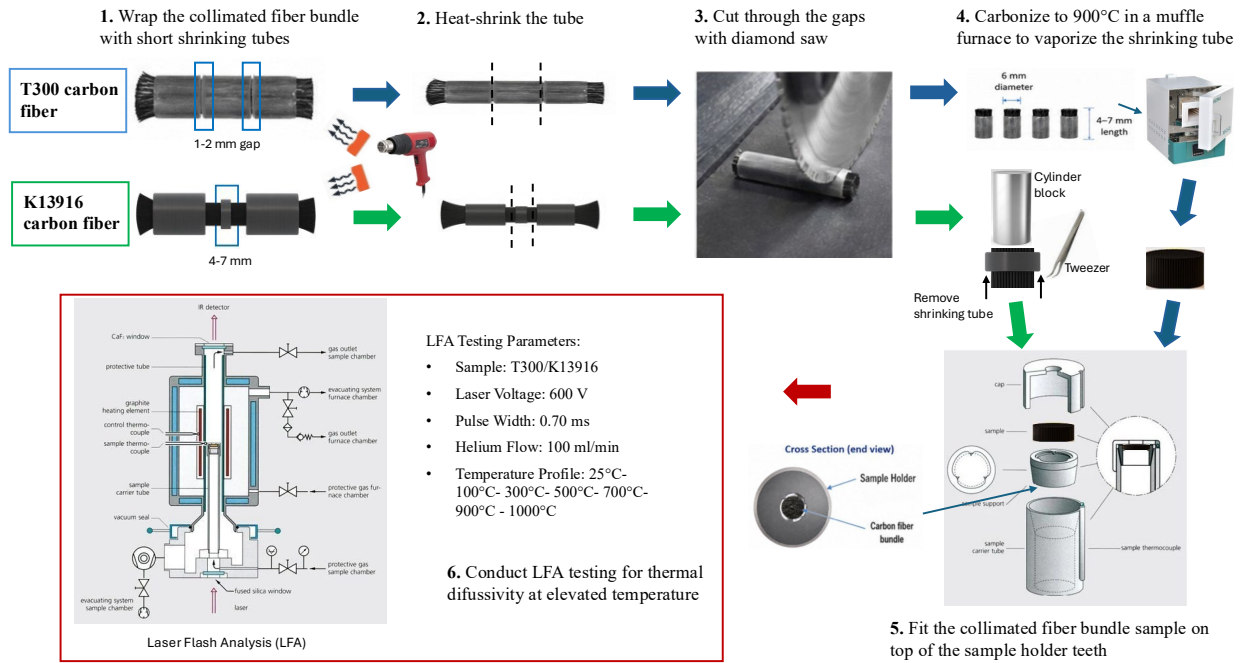


Figure 1: Carbon Fiber Sample Preparation Method for LFA

Property	Unit	T300		K13916	
		spec.	exp. (100°C)	spec.	exp. (100°C)
λ	W/(m·K)	10.5	9.948	200	234.128
c_p	J/g°C	0.777	0.791	0.866 ^a	0.944
ρ	g/cm ³	1.76	1.7602	2.16	2.1601
α	mm ² /sec	7.678 ^b	7.574	106.92 ^b	114.828

Notes:

- ^a Measured by STA at 50°C
- ^b Calculated
- The electrical conductivity of K13916 fiber is 2253.52S/cm, and the calculated thermal conductivity is ~331 W/(m·K) based on the formula by Lavin et al.(1993)

Figure 2: Thermal Conductivity Measurement Summary

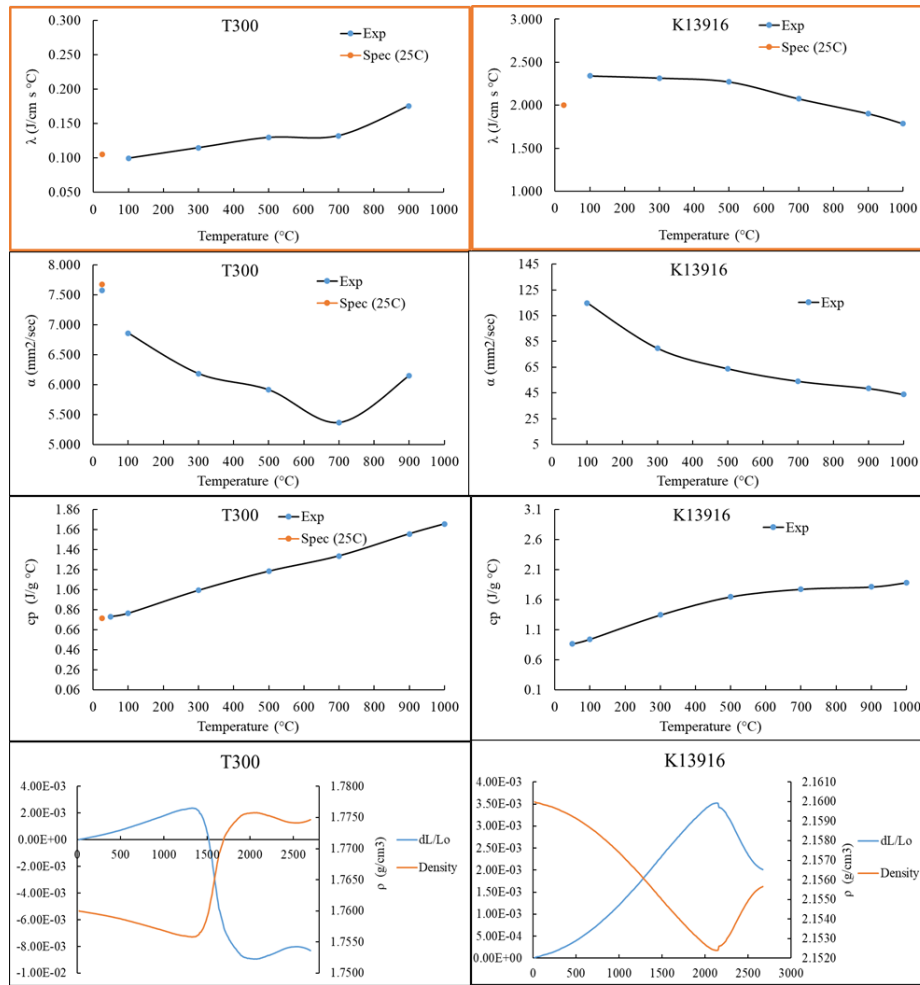


Figure 3: Thermal Conductivity Properties with Increasing Temperature

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Experimental Characterization of the Orthotropic Gas Permeability in High-Density Carbon-Phenolic Ablators During Pyrolysis

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Abstract

High-density carbon-phenolic ablators are critical components of thermal protection systems subjected to severe atmospheric reentry environments, where internal gas transport governs the pressure field, the blowing effect, and the risk of interlaminar spallation. This study experimentally characterizes the orthotropic Darcy permeability tensor of a high-density 2D woven carbon-phenolic composite, from its virgin state up to advanced pyrolysis (1000°C), using a steady-state flow methodology in a Hassler-type cell across the in-plane (IP) and through-the-thickness (TTT) material directions. At the virgin state, the woven architecture induces a pronounced structural anisotropy, with the in-plane permeability ($\approx 10^{-14} \text{ m}^2$) nearly an order of magnitude higher than the through-the-thickness permeability. While slip-flow (Klinkenberg effect) is detected at room temperature, its magnitude remains within the inherent mesoscopic material variability ($\approx 14\%$), justifying the use of a continuum Darcy model throughout the thermal campaign. As pyrolysis progresses, gasification of the phenolic matrix drives an exponential permeability increase exceeding two orders of magnitude, with the through-the-thickness permeability rising proportionally faster than the in-plane permeability, which in turn mitigates the initial anisotropy. The permeability evolution correlates robustly with the matrix mass loss fraction, enabling the extraction of orientation-specific exponential closure laws and the formal construction of orthotropic permeability tensors at both virgin and pyrolyzed states. These results provide direct, experimentally validated input data for multi-physics ablation solvers dedicated to thermal protection system design.

Keywords: carbon-phenolic, gas permeability, pyrolysis, thermal protection systems, ablation.

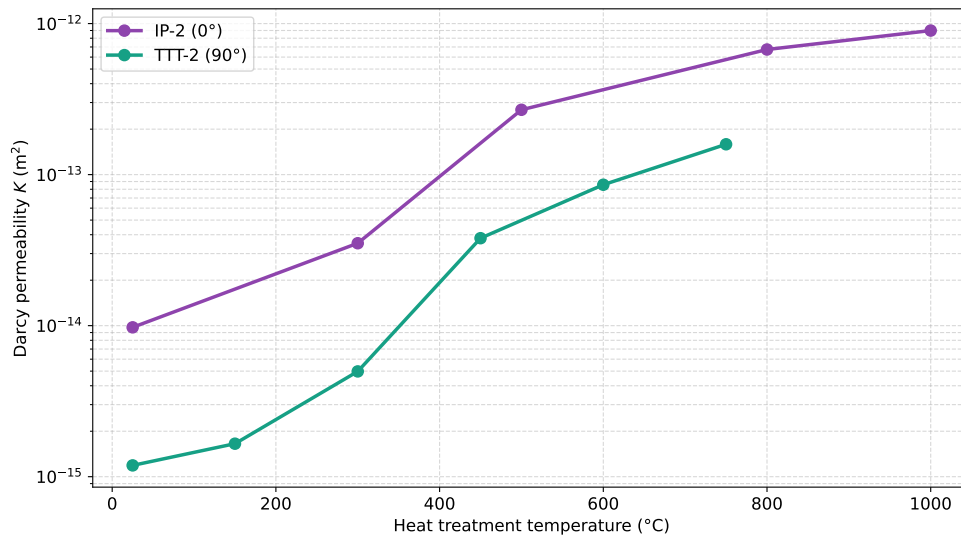


Figure 1: Thermo-structural evolution of the macroscopic Darcy permeability for the In-Plane (IP) and Through-The-Thickness (TTT) specimens.

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Staggered coupling of a high-order flow solver and a material solver for ablation in high-enthalpy flows.

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Abstract

Atmospheric re-entry subjects spacecraft to high heat load and a wide range of complex physico-chemical phenomena. The design of thermal protection systems therefore requires numerical tools capable of accurately modeling both the flow field and the material response. A comprehensive simulation must account for in-depth material reactions as well as near-wall gas-phase chemistry. However, the characteristic time scales of the flow and material processes differ significantly, making the use of a common time step inefficient, particularly because flow simulations are computationally expensive. As a result, the unified approach based on strong coupling can become expensive. In this work, a staggered coupling strategy between a flow solver and a material solver is proposed to overcome the limitations of standalone solvers. The proposed approach captures the coupled multi-physics interactions while reducing the computational cost of a fully unified solver [1], since the flow solution is updated only when changes in the material response significantly affect the external flow environment.

The flow solver, ArgoDG [2], computes the high-enthalpy aerothermochemical environment using a high-order discontinuous Galerkin discretization. The material solver, PATO [3], predicts the thermal and mechanical response of ablative materials, including heat transfer and pyrolysis. Recession of material and surface deformation are tracked using a moving mesh in the material solver and an immersed boundary method in the flow solver, avoiding the complexity and computational cost of remeshing the deforming fluid domain. At the fluid-material interface, coupled mass and energy balance boundary conditions are imposed to account for gas-surface interactions, including ablation, catalysis, and pyrolysis. The two solvers are coupled through the preCICE library [4], which manages data exchange, interface mapping, and interpolation. This modular coupling framework enables different flow and material solvers to be combined according to the desired physical models and numerical methods. In the present work, the steady-state flow solver of ArgoDG is coupled with PATO. The same framework can also be used to couple ArgoDG with its unified material solver, allowing both the flow and material domains to benefit from high-order discretization methods.

The coupling strategy and the underlying physical models will first be detailed. Their validation based on the numerical replication of an experimental campaign from the Plasmatron facility of the von Karman Institute (VKI) [5, 6] will then be presented.

Keywords: Ablation, staggered coupling, high-order method, Immersed Interface Method, Gas-surface interaction, high-enthalpy flow

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An Experimental Method for Measuring Gas Diffusivity and Tortuosity in TPS Materials

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Abstract

Thermal protection system (TPS) materials contain highly complex porous microstructures that create tortuous pathways for gas transport. Understanding these transport characteristics is essential for accurately understanding internal gas flow and thermal response in the high-temperature conditions experienced during atmospheric entry. Current methods for determining tortuosity exist for geological formations and only computational models have been developed for TPS materials. In this work, a novel experimental approach was developed to directly determine effective gas diffusivity and tortuosity from transient gas diffusion measurements using Zuram[®] as a representative TPS material. The results indicate a correlation between tortuosity, permeability, and char level providing insight into the relationship between pore structure and gas transport behavior. This methodology offers a new approach for experimentally characterizing gas diffusivity and tortuosity in TPS materials and may improve the accuracy of transport models used in thermal protection analyses.

Keywords: Thermal Protection System (TPS) Materials, Tortuosity, Permeability, Diffusivity

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Simulations of Yarn Micro-Mechanics of Woven Heat Shield Materials (3MDCP)

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Abstract

Carbon and phenolic fibers are commonly used in ablative thermal protection materials, such as 3-dimensional Mid-Density Carbon Phenolic (3MDCP), a 3D-woven composite comprised of mixed-fiber yarn bundles. Predicting the micro-mechanical response and fracture of twisted yarns composed of brittle and ductile fibers requires a modeling approach that captures per-fiber yielding, fiber fracture, and inter-fiber friction and contact. This work presents an extended bonded particle model (BPM) for discrete element method (DEM) simulation of fiber and yarn mechanics, implemented in LAMMPS. The model builds on the incremental bond formulation of Guo et al. and introduces a piecewise elasto-plastic constitutive law for axial extension, enabling representation of fibers that yield before failure. 3MDCP yarns were constructed using measured fiber radius distributions and helical twist geometry. Tensile simulations of single-ply 3MDCP yarns show good agreement with vendor stress–strain results. Fiber breakage models also show details on yarn breakage propagation, centered radially in the yarn. Yarn breakage of multi-ply 3MDCP also matched experimental observations in per-ply breakage; however, predicted yarn breakage strength were found higher than experimental observations.

Keywords: discrete element method, bonded particle model, yarn mechanics, thermal protection systems, 3MDCP

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Aerothermal Assessment of Supersonic Flows Past a Roughened Sphere-Cone

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Abstract

Prediction of roughness-induced aerothermal loading remains a major uncertainty in the design of re-entry vehicles because surface roughness can promote earlier boundary-layer transition and increase turbulent heating. Previous studies (e.g. Schneider, 2008, J. Spacecr. Rockets V 45, PP: 193–209) have established that surface roughness can increase turbulent heating on blunt-body and woven-pattern surfaces, whereas roughness-induced transition and compressible turbulence depend on local shock, separation, wake, vortex, and geometry-driven shock structures.

The present work performed aerothermal assessment of high-speed flow past a sphere-cone with a sinusoidal rough surface at the freestream Mach number $M_\infty = 1.5$ and Reynolds number $Re_\infty = 3000$, using high-fidelity direct numerical simulations. The smooth-wall case defines the reference aerodynamic and thermal environment and the rough-wall case is compared directly with the smooth-wall solution to evaluate how surface morphology modifies the external sphere-cone flow field and explain the underlying physics behind augmentations of turbulent heating at the roughened surface. The comparison focuses on wall heat flux, the Stanton number, rough-to-smooth heating augmentation ratio $q_{w,r}/q_{w,s}$, and rough-to-smooth Stanton-number augmentation ratio St_r/St_s . These quantities are interpreted together with flow-field diagnostics, including turbulent kinetic energy and Q -criterion, to connect surface heating augmentation to the underlying shock-turbulence-roughness interaction. By relating the aerodynamic features to the thermal metrics, the study provides a physics-based explanation of how roughness geometry alters the coupled aerothermal response of a sphere-cone capsule with a rough surface in supersonic flow.

Keywords: aerothermal loading, turbulent heating, wall heat flux, Stanton number

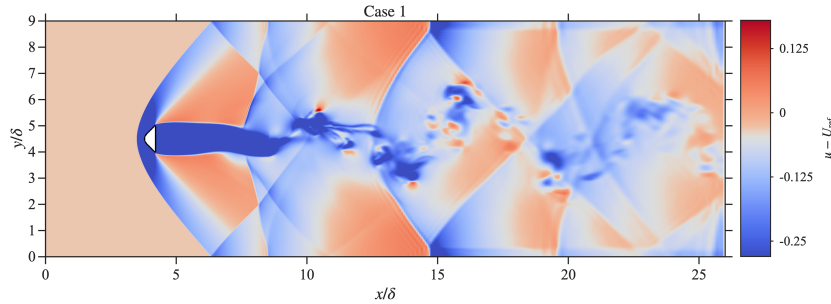


Figure 1: Instantaneous streamwise velocity contours for the smooth-wall sphere-cone at $M_\infty = 1.5$

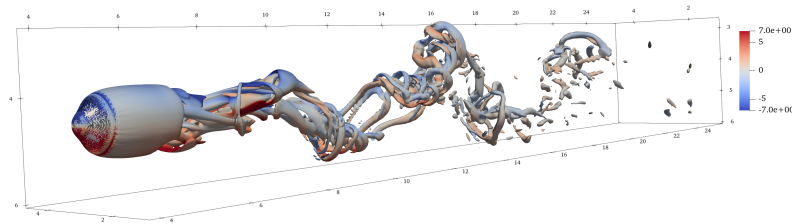


Figure 2: Q -criterion visualization for the smooth-wall sphere-cone at $M_\infty = 1.5$

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Aerothermal Characteristics of Supersonic Channel Flows Over Sinusoidal Roughness

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Abstract

Surface roughness and its effects on heat transfer are still an understudied area of high-speed aerodynamics. Wilder and Prabhu [AIAA Aviation Forum, 2019, ID: 20190028253] conducted hypersonic experiments comparing a smooth surface against two types of roughness surfaces: pattern and sandgrain. Their results showed heat augmentation caused by both of the roughness surfaces, with the sandgrain surface having the greater effect of the two with 1.11 to 1.66 times more heat augmentation than a smooth surface.

Understanding the impact that specific roughness topographies have on a surface's heat transfer is a key factor when designing and developing thermal protection systems. This study aims to perform and analyze supersonic flow simulations over a sinusoidal pattern roughness geometry at different Mach numbers and study their effects on heat transfer augmentation and important aerodynamic variables, such as the equivalent sandgrain height. The sinusoidal surface utilized for the simulations, similar to the pattern surface in the experiments performed by Wilder and Prabhu, is representative of the woven thermal protection developed by NASA's Heatshield for Extreme Entry Environment Technology [Annual International Planetary Probe Workshop (AIPPW), 2018].

Two direct numerical simulations were conducted. The simulations were performed for bulk Mach numbers of $Ma = 1.5$ and 3, and a Reynolds number of 3000 and 4880 respectively. Figure 1 shows the velocity divergence contour for both simulations. The roughness equivalent sandgrain height and turbulent Stanton number are analyzed, as well as their relationships with flow Mach number and roughness geometry. The results indicate a strong dependence of the aerothermodynamic features on the underlying roughness topography and its associated shock patterns.

Keywords: heat transfer, thermal protection systems, DNS

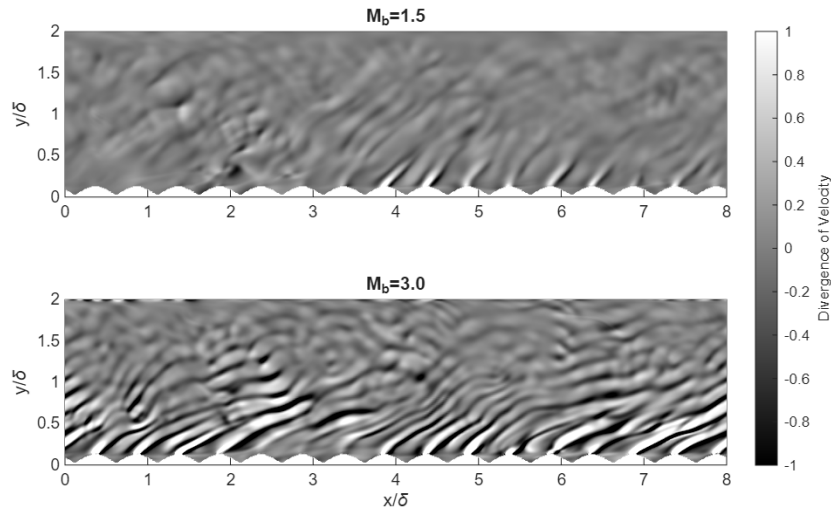


Figure 1: Divergence of Velocity Contour. $x - y$ plane contour plot for $z = 1.875\delta$

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Developing Digitally Knitted Textile Architectures for Thermal Protection Systems

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Abstract

Textile architecture is an important design variable in advanced thermal protection systems (TPS), where fiber arrangement and structural geometry influence permeability and, ultimately, gas transport within porous materials [1]. Advances in three-dimensional woven TPS, including the Heatshield for Extreme Entry Environment Technology (HEEET), have demonstrated the importance of engineered textile architectures for achieving specific performance objectives [2-4]. However, comparatively little research has explored digitally knitted textile architectures for candidate TPS materials.

Digital flatbed knitting provides a textile development platform in which material selection, yarn preparation, stitch topology, and multilayer geometry can be systematically designed, fabricated, and iteratively refined, providing stitch-level control over textile architecture [5-6]. This manufacturing approach enables rapid iteration of textile architectures while maintaining a continuous fabrication process that facilitates efficient exploration of structure–property relationships. Existing studies of knitted spacer fabrics have primarily focused on apparel [7], cushioning [8], and composite preforms [9], leaving the influence of knitted textile architecture on permeability for TPS applications largely unexplored.

The objective of this work is to establish an experimental framework for systematically investigating the influence of textile architecture on permeability in digitally knitted structures intended for future thermal protection system applications. Technical yarns are prepared through controlled twist insertion and fabricated into candidate structures using an industrial digital flatbed knitting machine [Figure 1]. Through iterative textile development, fiber material, stitch topology, spacer geometry, and yarn twist are systematically varied to establish stable, reproducible architectures suitable for permeability characterization.

The developed knitted textile samples described in this work establish an experimental platform for investigating the relationship between textile architecture and permeability in candidate thermal protection materials. This work provides a foundation for future permeability characterization, thermal characterization, computational modeling, and ablation studies.

Keywords: textile architecture, thermal protection systems, digital knitting

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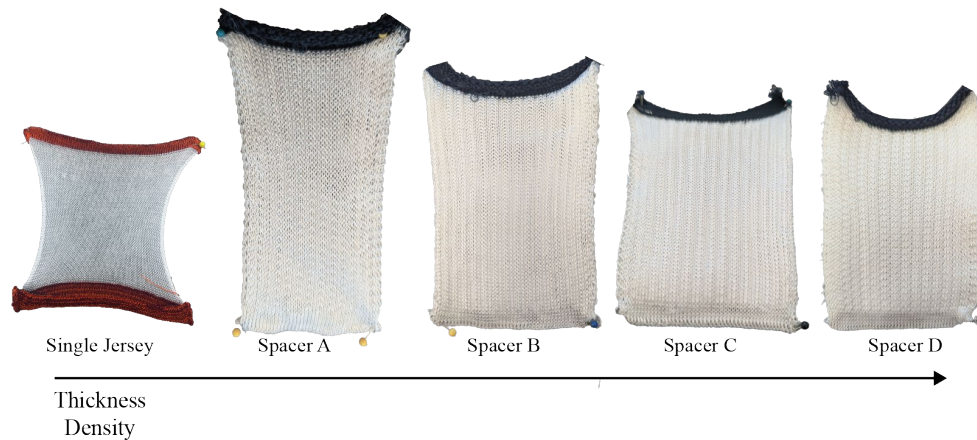


Figure 1: Iterative knit swatches, Single-layered jersey Nomex at left to increasing thickness and density of the structure through spacer yarn insertion (A to D).

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The evolution of transport properties in charring carbon-phenolic ablators

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Abstract

Carbon-phenolic ablators are critical for high-Mach-number flight resulting from ballistic atmospheric entry. Ablation phenomena occur simultaneously and are dependent on overlapping transport properties. Uncertainties in these properties necessitate large safety factors to ensure mission success. A linear progression of transport properties as a function of char extent (β) has been assumed historically, due to a lack of data between virgin and charred states. [1–3]

Linearity was examined experimentally using HARLEM ablators [4, 5]. The measured properties were porosity (helium pycnometry), and thermal diffusivity (laser flash method). β at intermediate states uses the definition in [3]:

$$\beta = \frac{\rho_v - \rho_s}{\rho_v - \rho_c}. \quad (1)$$

β for the virgin (v) and charred (c) states are, by definition, zero and one respectively. For intermediate char states (s), ρ_c was calculated using the resin char yield (thermogravimetric analysis), the resin mass fraction (from manufacturing), and the initial sample quantities. The measured properties progress linearly as a function of char extent (figure 1).

Keywords: charring ablators, transport properties, experimental

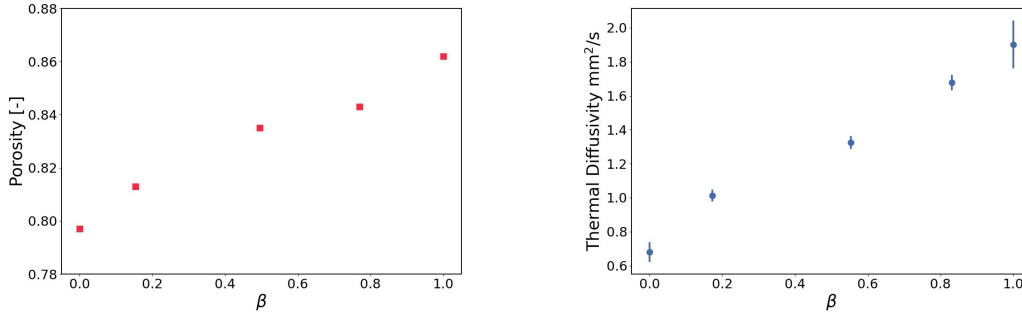


Figure 1: Transport properties

Acknowledgements

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Implicit coupling between free flow and pyrolyzing porous materials: from micro-CT-scale deformation to particle-scale interaction

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Abstract

Porous ablative materials undergo coupled thermal, chemical, and mechanical processes during atmospheric entry and other high-enthalpy environments. Heat transfer drives pyrolysis, gaseous products percolate through the porous skeleton and are injected into the surrounding flow, and the solid skeleton deforms as its composition and properties evolve. Porous-material response tools provide volume-averaged descriptions of pyrolysis and internal gas transport. A pyromechanical formulation was previously introduced to account for pyrolysis-induced deformation of the solid skeleton [1]. The present work extends this formulation by introducing coupled mass, momentum, and energy exchange with a resolved compressible gas flow.

The gas region is governed by the compressible Navier–Stokes equations, whereas the porous region is described by volume-averaged equations for pyrolysis kinetics, gas mass conservation, Darcy–Biot gas transport [2, 3], local-thermal-equilibrium energy conservation, and an incremental quasi-static momentum balance for the deforming solid skeleton. Conservative mass and energy interface conditions are derived from a moving control volume flux balance [4], while momentum coupling combines a normal traction relation with a Beavers–Joseph–Saffman tangential slip condition [5, 6]. The incremental displacement predicted in the porous region is transferred to the free-flow boundary, and an arbitrary Lagrangian–Eulerian mesh-motion problem propagates this displacement through the free-flow mesh while preserving conformity at the moving material interface [7].

The numerical implementation is carried out in the Porous material Analysis Toolbox based on OpenFOAM (PATO) through an implicit coupling between the material solver, the compressible free-flow solver, and the mesh-motion solver. Interface fields are exchanged through mapped boundary conditions, and the mass, momentum, and energy coupling at the moving free-flow/porous-medium interface is enforced using a fixed-point method, also referred to as a block Gauss–Seidel procedure [8].

The mass and momentum interface conditions are first verified using two free-flow/porous-medium benchmarks that isolate tangential and normal coupling effects. The Beavers–Joseph channel-flow problem assesses the tangential momentum condition and interfacial slip response, while the porous-plug configuration tests the normal mass balance, pressure transfer, and momentum coupling across a porous obstruction [9, 10].

The resulting framework is demonstrated for wood pyrolysis at the microstructure and particle scales. At the microstructure scale, the pyromechanical model is applied to assess whether pyrolysis-induced deformation can be predicted directly from wood micro-CT data. The segmented virgin micro-CT volume is used as the initial geometry of the cell-wall skeleton, which is modeled as a reactive, deformable porous continuum. Preliminary simulations show pyrolysis progression and the resulting deformation and morphological evolution of the solid skeleton. The numerically evolved microstructure will be compared with the corresponding experimentally pyrolyzed micro-CT volume using morphological descriptors and image-based permeability tensors. This comparison will provide a direct assessment of whether continuum pyromechanical deformation laws can predict the microstructural and transport-property evolution of pyrolyzing porous materials.

At the particle scale, the complete pyromechanical coupling with the resolved free flow is then assessed against the single-particle beech wood pyrolysis experiments of Gauthier [11]. The model reproduces the main trends in particle heating, mass loss, and anisotropic shrinkage, while also providing access to local fields such as the pyrolysis front, particle deformation, and flow redistribution around the particle. Particular attention is given to how the outward flow of pyrolysis gases affects heat transfer to the particle.

Keywords: pyrolysis, porous media, pyromechanics, strong coupling, ALE mesh motion, micro-CT

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Comparison of Fluid–Material Coupling Strategies for Hypersonic Ablation

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Abstract

Accurate prediction of ablative thermal protection systems requires a consistent description of the interactions between the external hypersonic flow and the material response. Surface heating drives pyrolysis, heterogeneous chemistry, and recession, while the injection of pyrolysis and ablation products modifies the composition, transport properties, and heat transfer within the near-wall flow. These coupled phenomena have motivated the development of numerical approaches in which the external flow and the material response are solved together rather than treated independently [1–5].

Several strongly coupled flow–material simulations have already been reported for hypersonic ablation, including finite-rate and nonequilibrium descriptions of the external flow and gas–surface interactions [2, 3, 6, 7]. Recent work has also highlighted the importance of the quantities exchanged at the fluid–solid interface and of the treatment of diffusive, advective, and reactive fluxes in historical, multi-element, and multi-species formulations [8, 9].

The present work presents a fluid–material coupling framework within the Porous-Material Analysis Toolbox based on OpenFOAM (PATO) [4]. The framework directly exchanges local physical quantities between an external hypersonic-flow solver and the material-response model. The fluid solver provides the wall pressure, fluid-side heat flux, near-wall temperature, density, species composition, and wall-normal distance. PATO advances the in-depth porous-material response and returns the wall temperature, pyrolysis-gas flux, ablation mass flux, injected-gas composition, surface-recession velocity, and updated interface position.

The coupling framework is used with Eilmer, an open-source multiphysics solver for hypersonic flows and high-speed aerothermodynamics [10]. The interface includes multicomponent species diffusion and finite-rate heterogeneous surface chemistry. Thermochemical and transport properties, together with surface reaction rates, are evaluated using Mutation++ and a user-defined ablation mechanism [11, 12]. An element-based equilibrium formulation is also implemented within the same boundary-condition framework. In this formulation, elemental mass balances are solved at the surface and the corresponding equilibrium species composition is reconstructed using Mutation++. This enables equilibrium gas–surface chemistry to be evaluated locally within the same coupling framework, avoiding the use of precomputed surface tables.

The proposed methodology is assessed on a transient cylinder test case representative of atmospheric-entry conditions. The objective is to compare the classical B'/Z^* -based transfer formulation currently available in PATO, which represents gas–surface coupling through boundary-layer transfer quantities and an elemental formulation of multicomponent transport [1, 8], with a direct fluid–material coupling based on the exchange of local thermochemical quantities between the flow and material solvers. The comparison focuses on the evolution of wall heat flux, wall temperature, pyrolysis-gas injection, surface composition, recession, and computational cost. Particular attention is given to identifying the physical differences between the two coupling strategies and to discussing the conditions under which these differences become significant. Although demonstrated here on a canonical test case, the proposed framework is intended for future application to realistic atmospheric-entry configurations such as the Mars Science Laboratory heatshield [5–7].

Keywords: fluid–material coupling, thermal protection systems, hypersonic ablation, gas–surface interaction, B' formulation, Z^* formulation, finite-rate chemistry

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Dragonfly TPS Challenges

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Brief Presenter Biography

Michael Wright has worked at NASA Ames for 28 years focused on EDL, particularly aerothermodynamics and TPS. He is currently the Dragonfly EDL Phase Lead and serves concurrently as the Agency EDL strategic capability lead.

Abstract

Dragonfly, NASA's fourth New Frontiers mission, will deliver a rotorcraft to Titan for mobility and repeated in-situ science. This talk will discuss the Thermal Protection System design for the mission and highlight challenges encountered as the design has matured. The heatshield material is a "heritage" heatshield thermal protection material called PICA, that was being used well within qualified limits. However, this was a new variant, called PICA-D. Its thermal properties were in family with previous versions, but when the thermostructural data started to arrive it showed this new material was significantly more brittle than its predecessors. This led to predicted negative margins in the finite element analyses and drove us to a third tiger team to vet the material and develop novel test-based techniques to qualify our ultimate design for Titan flight. The backshell material is SLA-561V, which had to be requalified for this mission due to Lockheed moving material production from Michoud to Denver. The requalified material has consistently been higher density than its predecessor, which has led to some issues with confirming the material for flight. The RF transparent material for the antenna Radome is Acusil-II. Although this material also has high heritage, we have had challenges with closing our design due to significant aeroheating and ambiguities in the material model.

Shock tube - plasma wind tunnel similarity based on optical emission spectroscopy

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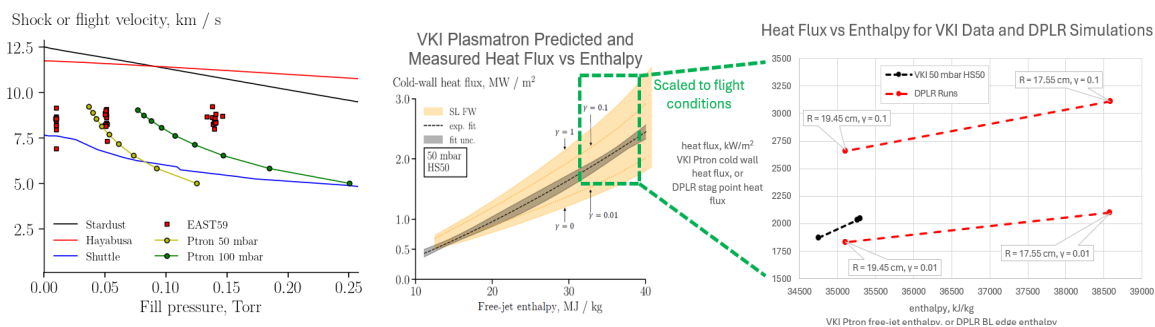
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The Electric Arc Shock Tube (EAST) is an impulse facility that duplicates hypersonic shock waves relevant to kinetics and radiation studies [1]. By matching free-stream density and shock velocity, a similarity in particle time with the post-shock flow is achieved [2]. Optical Emission Spectroscopy (OES) is one major experimental diagnostic employed to characterize the thermochemical state of the gas and infer the radiative heating contribution through numerical simulations of the non-equilibrium flow. Plasma Wind Tunnels (PWT), such as the Plasmatron facility at the von Karman Institute for Fluid Dynamics, provide a ground duplication of the stagnation line Boundary Layer (BL) flow, relevant to experimental gas-surface interaction and ablation studies [3]. Using OES, an improved framework for the ICP jet characterization has been recently developed [4], thus allowing more accurate ground-to-flight duplication.

This poster investigates the applicability of both similarity approaches to the same flight condition. Starting from available data sets, scaled flight parameters corresponding to available PWT data are computed, as shown in Fig. 1. Conditions close to those available from EAST data are then selected. DPLR simulations are run on an equivalent sphere, with a scaled flight radius, and a wall temperature of 350 K. Results show that the computed wall heat flux for recombination coefficients between 0.01 and 0.1 is close to the experimental PWT data. However, due to the small flight radius related to these particular conditions, the shock layer is thin, and equilibrium is not reached at the BL edge. This would prevent a correct BL duplication, as well as the determination of the corresponding shock tube conditions. The study suggests targeting higher shock layer pressures, allowing for faster equilibration and larger shock stand-off distances. Finally, the poster will investigate how the methodology can be employed to provide validation of both radiative and convective heating against experimental data collected in both facilities.



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Modeling volumetric oxidation and oxidation-induced mechanical degradation in porous graphite TPS

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Abstract

Thermal protection systems (TPS) face extreme thermo-chemo-mechanical loads during atmospheric re-entry. Carbon-based materials, such as carbon/carbon composites and graphite, are widely used in TPS applications because of their high strength-to-weight ratio and refractory properties; however, they undergo significant material ablation. Many state-of-the-art computational models underpredict experimental recession rates. This discrepancy is largely attributed to volumetric oxidation [1]. In addition to impacting the recession rate, volumetric oxidation degrades the material's structural integrity [2], which can lead to mechanical failure. This paper investigates the coupled thermo-chemo-mechanical effects of volumetric oxidation in porous graphite using the multiphysics finite element software Σ MIT. We resolve the solid heat transfer, gas diffusion through the porous medium, and heterogeneous solid-gas chemistry both within the bulk and at the external surface. Since volumetric oxidation occurs on the internal pore walls [3], the finite-rate air-carbon ablation (ACA) chemical kinetics model is used to model volumetric oxidation in addition to external surface oxidation. As the volumetric oxidation progresses, the porosity and apparent density evolve, degrading the mechanical properties of the material. The reduction in the elastic modulus and three-point bend strength with increasing porosity is modeled using an exponential decay model. The coupled framework is validated against experimental data from Kane et al. [4], in which, for a fixed mass loss, several porous graphite cylinders are oxidized at different temperatures. These temperatures span multiple volumetric oxidation regimes, as characterized by the nondimensional Thiele modulus. The multiphysics framework developed in this paper successfully reproduces the post-oxidation failure strength in a three-point bend test and predicts the geometric change in the graphite cylinders. Furthermore, we present multiple numerical examples, with and without volumetric oxidation-induced mechanical degradation, to demonstrate the impact of volumetric oxidation on the material's mechanical response. Overall, this work underscores how oxidation and material failure are inextricably linked in porous graphite and illustrates the value of a multiphysics approach in predicting their material response.

Keywords: volumetric oxidation, multiphysics, graphite, porous medium, thermal protection systems

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Aerothermal Modeling of 2.5DCC in H1 Arc Heater

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Abstract (ITAR Track)

RTX is leveraging mature commercial manufacturing infrastructure and capabilities to produce Carbon/Carbon (C/C) Structures at rate for the next generation of hypersonic programs. As this process matures, RTX is testing other material variations including ways to increase carbon density to survive high pressure and heat flux conditions seen in flight conditions like ballistic reentry. This presentation provides the modeling efforts completed to match the data collected at the Arnold Engineering Development Complex (AEDC) H1 Arc Heater and compares the high density 2.5D C/C response to traditional 3D C/C.

Keywords: ablation, carbon, thermal protection systems

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Aerothermal Evaluation of 2.5DCC in H1 Arc Heater

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Abstract (ITAR Track)

RTX is leveraging mature commercial manufacturing infrastructure and capabilities to produce Carbon/Carbon (C/C) Structures at rate for the next generation of hypersonic programs. As this process matures, RTX is testing other material variations including ways to increase carbon density to survive high pressure and heat flux conditions seen in flight conditions like ballistic reentry. This presentation provides test data collected at the Arnold Engineering Development Complex (AEDC) H1 Arc Heater and compares the high density 2.5D C/C response to traditional 3D C/C.

Keywords: ablation, carbon, thermal protection systems

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A Novel Thin-Layer Model for Finite Rate Ablation Closure

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Abstract

Legacy film-theory and equilibrium assumptions have historically been adequate for ablation modeling relevant to ballistic reentry. Finite-rate ablation chemistry is being pursued as hypersonic flight trajectories incorporate reaction-limited regimes. The SPARC code of Sandia National Laboratories has a research capability for finite rate ablation, but this requires complex gas models and is not yet a viable workhorse engineering capability. We present a novel approach to incorporating finite rate ablation which sidesteps the cost of computational fluid dynamics (CFD) with many species and challenging boundary conditions. This approach also readily fits into pre-tabulated ablation models with lower-fidelity integral boundary layer methods. We refer to this physics-based thin-layer approach as the *surflet* model, analogous to similar non-premixed *flamelet* models of combustion. The surflet model is grounded in transforming the thin-layer governing equations into boundary value problems in composition space, coupling non-equilibrium boundary layer chemistry and finite-rate heterogeneous kinetics. We demonstrate the ability of this approach to accurately model stagnation-point ablation and viscous heating, with comparisons to CFD with finite rate ablation in the oxidation regime and arc jet validation data in the sublimation regime.

Keywords: ablation, surface chemistry, thermal protection systems

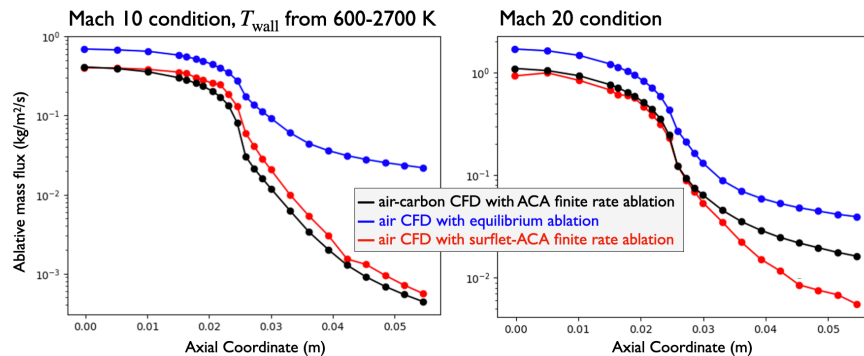


Figure 1: Comparisons of oxidation-regime ablation predictions on a generic blunt wedge geometry at two Mach numbers. Predictions include those of detailed air-carbon transport with coverage-dependent finite rate ablation (ACA mechanism, see [1]), 5-species air CFD with equilibrium ablation via film theory, and a 5-species air model with surflet-based ablation based on the ACA mechanism.

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Probabilistic inference of air-carbon ablation model parameters using conditional flow matching

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Abstract

Air-carbon ablation models are central to predicting the thermochemical response of carbon-based thermal protection systems during atmospheric entry. However, existing finite-rate air-carbon ablation (ACA) models contain numerous reaction-rate parameters whose values are primarily calibrated using molecular beam scattering experiments performed under near-vacuum conditions, introducing uncertainty when extrapolated to practical hypersonic environments. At the same time, recent flow-reactor experiments have provided complementary experimental data under conditions more representative of hypersonic applications. In this work, we make use of flow reactor experiments to infer parameters of the ACA model by leveraging a data-driven generative framework. A numerical analog of the flow-reactor experiment is first employed to generate a large synthetic dataset by sampling from the prior distribution of the ACA parameters and evaluating the corresponding carbon mass fluxes at multiple surface temperatures. These synthetic parameter-measurement pairs are then used to train a conditional flow matching algorithm (Fig. 1(a)) to generate samples from the posterior distribution (Fig. 1(b)) of the ACA parameter vector, conditioned on mass-flux observations. Once trained, the generative model performs posterior inference using the experimentally measured carbon mass fluxes. The proposed framework generates iid samples from the posterior distributions rather than producing single best-fit estimates, enabling rigorous quantification of parameter uncertainty and correlation. Compared with conventional calibration approaches, the proposed methodology provides orders-of-magnitude faster inference and establishes a probabilistic framework for updating gas-surface chemistry models as new experimental measurements become available.

Keywords: Material response, ACA model, Bayesian inference, inverse problems, generative algorithms

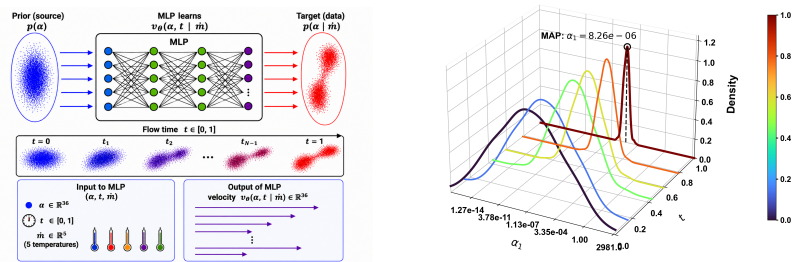


Figure 1: A multi layer perceptron (MLP) uses the synthetic dataset to train the generative model (Fig. 1(a)). The velocity vector obtained from the MLP is used to evolve samples from a Gaussian source to the desired posterior distribution of ACA parameters (Fig. 1(b)).

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A Poro-Thermo-Mechanics Theory for Fracture and Delamination of Carbon Ablators

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Abstract

We propose a thermo-chemo-mechanics model suitable for the description of poromechanical failure in thermal protection system ablative materials. The approach is based on a unified discontinuous Galerkin formulation of the heat transfer, the pore fluid generation and transport processes as well as the mechanical deformation, which may include crack nucleation and growth. In the first portion of this talk, the methodology is verified in the absence of crack propagation, and qualitative validation against observations of poroelastic fracture is presented. Large-scale, fully-coupled analysis of post-fracture gas pressure relief is enabled, offering the capability to analyze pore-pressure induced failures of the kind recently observed on NASA's Orion spacecraft. Then we identify nondimensional groups controlling the competition between gas generation, transport, mechanical stress, and fracture, and use large-scale simulations to quantify the fundamental role of material permeability on the onset of crack nucleation, the through-thickness propagation, and the lateral crack spacing. The improved understanding of ablative material response to reentry may be important for the design of future thermal protection systems.

Keywords: Multiphysics, Hypersonic, Fracture

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Thermomechanical modeling of woven materials with particle-based, explicit-fiber simulations

(Ablation Workshop 2026)

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ABSTRACT

Fiber-based materials are extensively used to protect spacecraft during entry. Insulative fibers, often in a fiber network or woven, provide rigidity, strength, and control of material anisotropy and density. Woven thermal protection materials, such as ADEPT (Adaptable, Deployable Entry and Placement Technology), 3D-MAT (3-Dimensional Multifunctional Ablative Thermal Protection), and 3MDCP (3D Woven Mid-Density Carbon Phenolic), enable missions with stronger and denser materials for entry profiles with high shear and heat flux. Vulnerabilities to woven thermal protection materials include manufacturing-induced material property variation, and impact from micrometeoroids. Simulating woven materials under these conditions require models that can resolve hierarchical structures, thermomechanical behavior, and failure.

To address this, we simulate weave thermal conduction and mechanical deformation. We simulate the full weave with a coarse-grained yarn model is presented. The model combines a validated, high-resolution single 3MDCP yarn model and phenolic resin model. Instead of modeling every fiber, each yarn ply with order 10, instead of order 1000, fibers. The discrete element bonded particle model (DEM-BPM) of fibers captures the thermal and mechanical behavior within and between fibers. We study the proportion of heat transfer and stress via the contact network, fiber bonds, and overall weave geometry.

An Iterative Coupling Methodology for Fully Coupled Pyrolysis, Gas–Surface Interaction, and Thermo-Structural Analysis

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Abstract

We developed a fully coupled multi-physics simulation framework for high-fidelity modeling of thermal protection system (TPS) ablation by integrating fluid dynamics, thermal response, pyrolysis, structural mechanics, and chemical processes within a unified environment. The framework couples the US3D flow solver with the KATS material response solver, enabling simultaneous prediction of heat transfer, pyrolysis gas generation and transport, surface recession, and structural deformation. The thermal and structural solvers share a common computational mesh, allowing consistent evaluation of temperature-dependent stresses, strains, thermal expansion, and internal pressure effects for both isotropic and orthotropic materials, while accounting for material variability and uncertainty. During each coupling interval, the thermal response and pyrolysis solutions update the material state and fluid boundary conditions, after which the flow field is recomputed. If the fluid solution does not converge, an implicit coupling strategy iteratively updates the thermal and pyrolysis response within the same interval, providing a robust and accurate prediction of the coupled fluid-material interaction during TPS ablation.

Keywords: Coupling

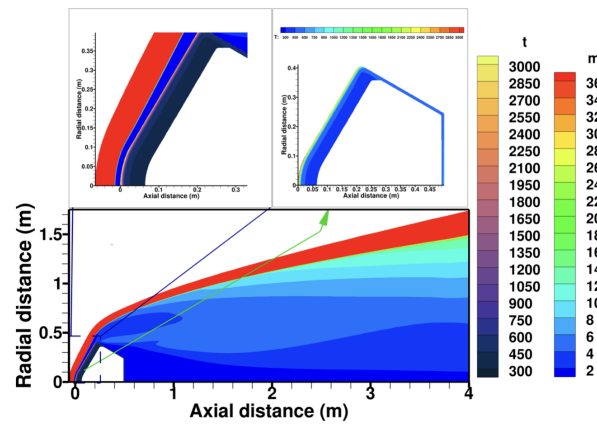


Figure 1: The US3D-KATS coupled simulation Stardust capsule

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Thermo-poro-mechanical modeling of RTV intumescence

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Abstract

Room temperature vulcanizing (RTV) silicone is a high-temperature adhesive used as a gap-filler between heatshield tiles in numerous entry missions. Its propensity to intumesce, or swell upon exposure to heat, is a well-known effect that needs to be carefully quantified during design. At tile interfaces of charring ablators, intumescence, combined with differential recession, could cause the gap filler to protrude past the ablator outer mold line, forming a “fence”. Fencing can in turn cause transition to turbulence of the flow around the heat shield, leading to augmented surface heating. Recent experiments conducted at the Plasmatron X facility, the high enthalpy wind tunnel at the Center for Hypersonics and Entry Systems Studies, have shown prominent fencing of RTV gap fillers in PICA, under both nitrogen and air plasmas [1,2]. Similar observations are well known in the arc-jet literature. Further experiments under controlled environment, performed using *in situ* X-ray micro-computed tomography (micro-CT) at the Advanced Light Source (ALS), have shown heating rate-dependent swelling and shrinkage of RTV during pyrolysis [3–5].

To simulate RTV intumescence, a novel model was introduced in the Porous Materials Analysis Toolbox based on OpenFOAM, PATO [6], to account for pore-pressure buildup within both closed- and open-pores [7]. The governing equation for the thermo-poro-mechanical response were developed, assuming linear elasticity for the charring silicone. A new *multi-pyrolysis* model that tracks non-monotonic advancement of material properties with pyrolysis was proposed. This model addresses the limitations of state-of-the-art ablator models to capture the different stages of thermal degradation and coupled thermomechanics.

Swelling of RTV was simulated using the new thermo-poro-mechanical model and compared against *in situ* micro-CT data. Results showed good agreement in intumescence height and temperature profiles at all heating rates, indicating that the key factor contributing to RTV swelling is the internal pressure build-up within closed- and open-pores. As RTV is cured into a soft (rubbery) compound with low-porosity and permeability, initial temperature increase and pyrolysis gas production cause a significant increase of internal pressure, causing a pronounced volume growth. As thermal degradation progresses, rigidization of the silicone occurs due to char hardening which counteracts volume shrinkage after gas pressure relief. Overall, our model shows that accounting for changes in properties such porosity, permeability and key thermomechanical coefficients is crucial for capturing the RTV volume change during ablation and enables a predictive capability for heatshield gap-filler response. A plan for future calibration of thermomechanical properties evolution during degradation is discussed, as a key next step to close the new model.

Keywords: *silicone intumescence, thermo-poro-mechanical material modeling, micro-tomography, thermal protection system*

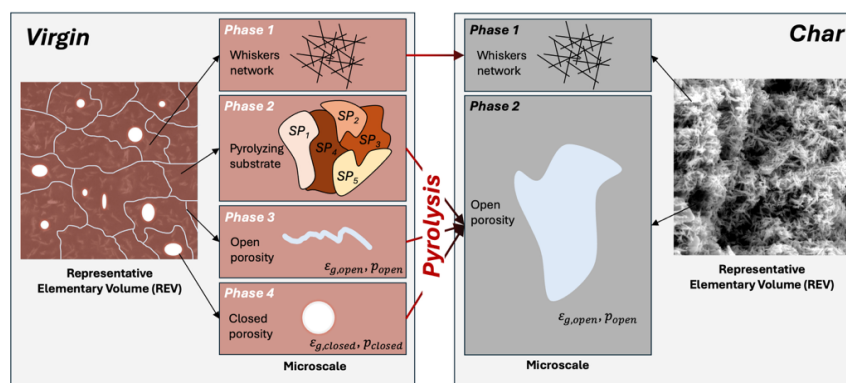


Figure 1: Representative elementary volume (REV) of virgin and charred RTV.

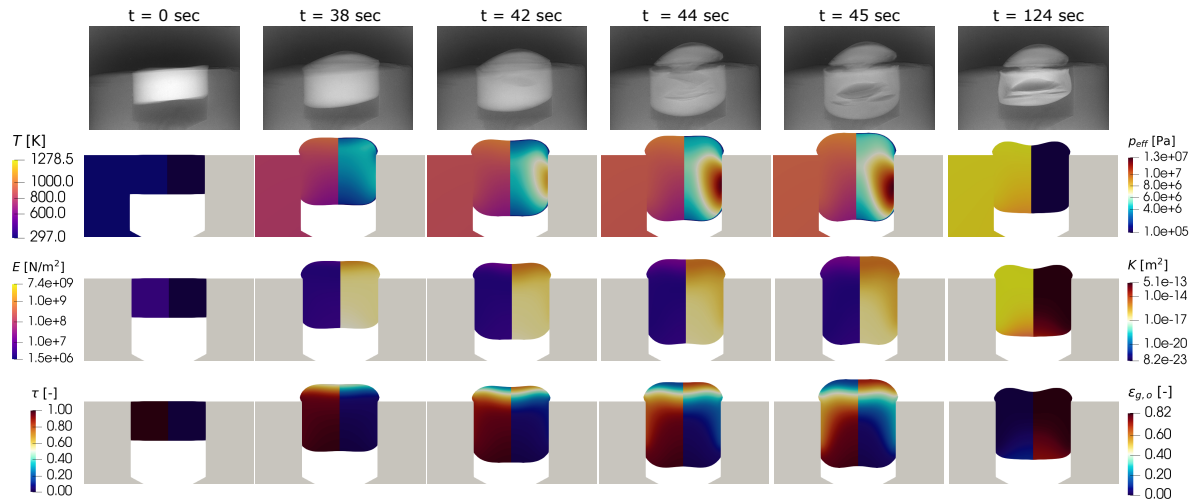


Figure 2: Thermo-poro-mechanical simulations at 1946 °C/min compared with radiographs at selected time points. Contours show temperature and effective pressure, Young's modulus and permeability, advancement of pyrolysis and volume fraction of open porosity, respectively.

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Modeling and simulation of radiometer placement experiments in the NASA Ames mARC II arc jet facility

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Abstract

During the NASA Mars 2020 [1] and Artemis I [2] missions, re-entry capsules utilized radiometers to measure shock layer radiation, an important contributor to the total vehicle heating. While the sensor in the Mars 2020 architecture was flush mounted into the vehicle backshell, Artemis I featured a stagnation-region placement with the sensor located at the bottom of a cavity. Post-flight data from both missions revealed unexpected signal attenuation [3], hypothesized to result from heat shield ablation products depositing onto the radiometer window. To investigate this phenomenon, experimental tests were developed for the the NASA Ames mARC II arc jet facility to replicate both flight configurations. This study utilizes CFD simulations to inform the design of the mARC II tests and to characterize the underlying aerothermodynamic and deposition physics.

This presentation will describe the modeling and simulation of experiments in the mARC II facility, aiming to reproduce ablation product deposition in small cavities under flight-like scenarios. To model this, both uncoupled and coupled simulations were performed, utilizing the US3D hypersonic flow solver [4] and the ICARUS material response solver [5], with the ARES framework [6] employed to couple the two tools. This has been done both to understand problems related to past cavity designs and to investigate new cavity configurations aiming to reduce ablation product deposition in future flight missions. [7].

Keywords: thermal protection systems, cavity flow, ablation, coupling, arc-jet

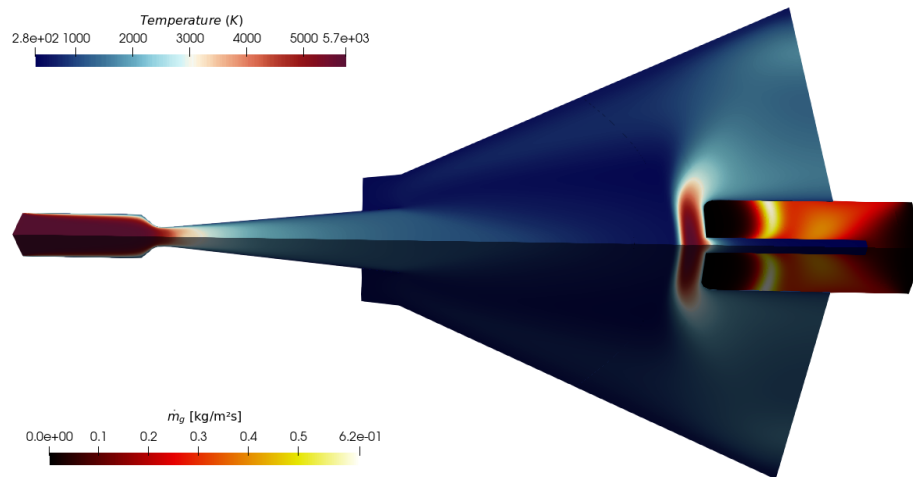


Figure 1: Uncoupled simulation of the flow in the mARC II facility, using a flat-face sample. This case aims to represent the sensor placed in a cavity on the forebody of the Artemis I vehicle. The flow simulation was run to a steady solution, and the results were used as boundary conditions for the transient material simulation. The material simulation was run for 90 s of real time, mimicking the mARC II test duration. The instant represented in the picture depicts the sample ablation after 40 seconds.

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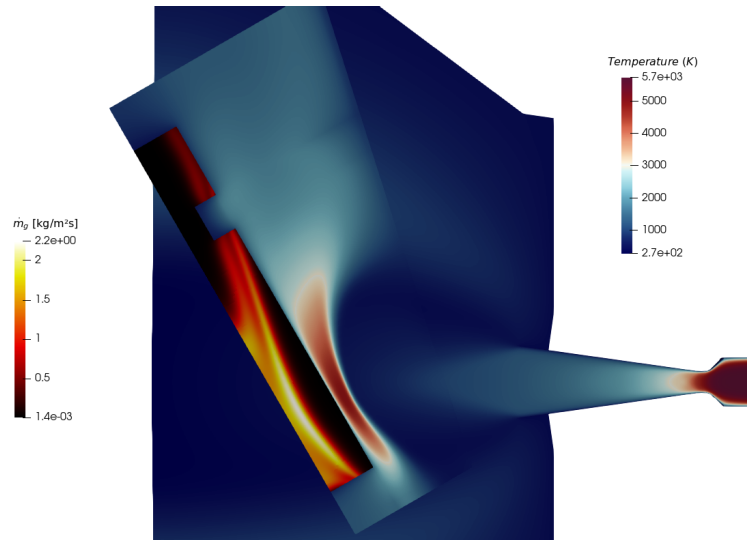


Figure 2: Uncoupled simulation of the flow in the mARC II facility, using an inclined flat plate. This case aims to represent the sensor placed in a cavity on the backshell of a vehicle. The flow simulation of the mARC II facility with no test article was run to a steady solution, which was used to extract boundary conditions for a subdomain containing the flat plate. A subsequent simulation of the subdomain containing the flat plate was run to a steady solution. The material simulation was then run for 90 s of real time, with the instant represented in the picture depicting the sample ablation after 40 seconds.

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Machine learning-accelerated embedded chemistry calculations for the simulation of oxidation transitions in silicon carbide TPS

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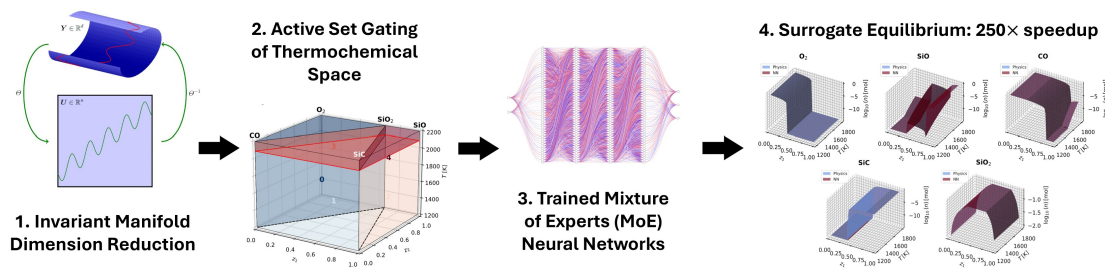
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Abstract

In hypersonic environments, SiC-based Ultra-High-Temperature Ceramics (UHTCs) suffer from intricate failure mechanisms that involve transitions across oxidation regimes and coupled thermo-chemo-mechanical processes. When reactions are fast relative to transport, these transitions — along with chemical speciation rates within each regime — can be predicted by performing embedded Gibbs Energy Minimization (GEM) calculations at every point in space and time within a multiphysics simulation. However, this often involves billions of GEM solves at an extreme computational cost — up to 99% of simulation time. Machine learning surrogates for GEM promise large speedups, but in practice often require prohibitively large training datasets. Furthermore, they suffer from catastrophic rollout error in embedded contexts, as small violations of element conservation or species non-negativity can accumulate over time steps. In this work, we present a neural network surrogate for embedded GEM that simultaneously addresses these limitations. The key idea is that the network is formulated in a dimensionally-reduced thermochemical state space that enforces physical constraints by construction, and decreases training data requirements by six orders of magnitude. To alleviate difficulties in training across sharp oxidation transitions, a phase-aware, analytically gated mixture-of-experts architecture is used, with additional inductive bias enforced via the Gibbs phase rule. We specialize the surrogate to the SiC/O₂ system and deploy it within the fully coupled thermo-chemo-mechanical framework recently proposed by the authors (Rulko & Radovitzky, *JACerS* 2026). Verified against direct GEM in Cantera, the surrogate achieves exact element conservation and an absolute error below 10^{-5} mol/mol with $\sim 7\times$ and $\sim 250\times$ speedups on CPU and GPU, respectively. Embedded in long-horizon simulations, its relative rollout error in the macroscopic quantities of interest remains bounded below 0.1%, and the resulting predictions of ablation rate, oxide growth kinetics, and the active-to-passive transition boundary retain quantitative agreement with experiments.

Keywords: Neural networks, manifold dimension reduction, Gibbs energy minimization, silicon carbide, embedded chemistry, multiphysics, oxidation, ablation



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Under Pressure: The Artemis I Heatshield Char Loss Investigation and Artemis II's Successful Entry

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Abstract

Following the successful Artemis I skip reentry on December 11, 2022, unexpected char liberation from the Orion heatshield prompted the formation of an Anomaly Response Team to determine the root cause and establish flight rationale and corrective actions for subsequent missions. Through a comprehensive investigation including detailed hardware analysis, modeling & simulation, and ground testing, the team determined that the low permeability Avcoat experienced extreme internal gas pressure buildup during the skip entry, leading to crack formation and char liberation. Key discoveries included significant performance differences between permeable and impermeable heatshield regions and successful replication of the anomaly through ground testing. Based on extensive ground testing and analysis, Artemis II flew a modified trajectory without the skip entry to minimize crack-inducing conditions, and successfully splashed down on April 10, 2026 with significantly reduced char loss. For Artemis III and beyond, a corrective action was implemented to produce a more permeable version of Avcoat that will substantially reduce internal pressure accumulation during entry.

Keywords: Orion Heatshield, Avcoat, Thermal Protection Systems, Char Loss

References

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Spatially resolved emission spectroscopy around graphite samples in nitrogen/methane plasmas

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Abstract

Dragonfly is set out for Titan, Saturn's largest moon, for exploration. The spacecraft is expected to experience significant radiative heating during the EDL phase of its journey. Unlike most atmospheric (re)entry vehicles, where convective heating is the dominant mechanism, Dragonfly's heating is expected to be dominated by radiative heating. This is due to the formation of cyano radical behind the bow shock through the recombination of carbon and nitrogen atoms. The CN radiates in both the violet ($B^2\Sigma^+ \rightarrow X^2\Sigma^+$) and red ($A^2\Pi \rightarrow X^2\Sigma^+$) band. Although several studies have investigated CN formation under non-equilibrium conditions, relatively few have examined its chemical kinetics under equilibrium conditions [1–3]. Studying CN radical formation under equilibrium conditions is important not only for understanding of its chemical kinetics and improving thermal protection system design but also for reducing uncertainties in the CFD models. In this study, optical emission spectroscopy was used to investigate CN formation in the boundary layer of a graphite sample exposed to nitrogen and nitrogen/methane plasma in both the UV and Vis/IR spectral regions. A Shamrock 500i imaging spectrometer with a Pixis 400X camera was used to image the emission spectra. Abel inversion was performed to obtain spatially resolved spectra along the radial direction. The experiments were conducted at 380 Torr using a gas mixture consisting of 98.5 % N_2 and 1.5 % CH_4 . The measured spectra were compared with predictions from the NEQAIR line-by-line spectral radiation code to determine the equilibrium temperature at multiple radial locations across the plasma. The CN red band was not observed in the boundary layer of the graphite sample exposed to pure N_2 plasma; however, the CN violet band was evident in the boundary layer. In contrast, for the N_2/CH_4 plasma, CN emissions were prominent in both the red and violet bands, with and without the graphite sample. The radiation emitted by the N_2/CH_4 plasma was greater than that from the pure N_2 plasma, attributable to higher CN concentration. The Abel-inverted experimental spectra showed good agreement with the emittance computed via NEQAIR. The maximum temperature was estimated to be 3678 K at the centerline of the N_2/CH_4 plasma, corresponding to the location of the highest CN concentration. Both temperature and CN concentration decreased monotonically with increasing radial distance.

Keywords: CN radical, equilibrium, optical emission spectroscopy, Abel inversion

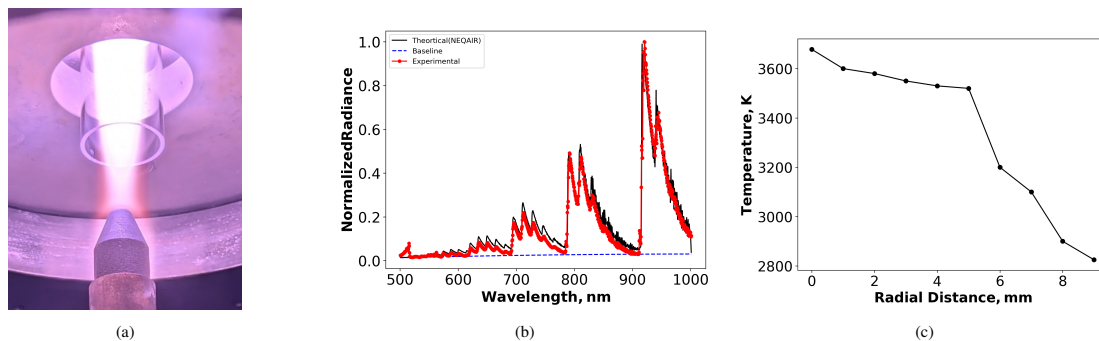


Figure 1: (a) Graphite sample exposed to N_2/CH_4 plasma. (b) Spectral fitting between the normalized Abel-inverted experimental data and emittance computed from NEQAIR (c) Radial temperature distribution obtained after Abel inversion and spectral fitting.

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Dust Effects on the Aerothermal Environment and TPS Material Response during Martian Hypersonic Entry

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Abstract

During Martian atmospheric entry, suspended dust particles impact the vehicle at high speed, adding collisional heating and mechanical erosion to the thermal protection system (TPS) beyond conventional aerothermal loads. During global dust storms, particles rise above 40 km, making these effects relevant over much of the entry trajectory. This work quantifies the combined effect of dust on the aerothermal environment and TPS material response using a multi-solver framework that couples a thermochemical non-equilibrium flow solver (HEGEL) [1], a Lagrangian particle solver (ORACLE) [2], and a material response solver (PATO) through preCICE [3]. The CFD–material response coupling is validated against the arc-jet graphite ablation case of Zibitsker et al. [4], reproducing the measured surface and in-depth temperature histories; the particle solver was verified separately [2]. HEGEL, interfaced with the PLATO thermophysical library [5], resolves the two-temperature flowfield; ORACLE returns two-way coupled source terms together with wall-collision heat flux and crater-based mechanical recession; PATO computes the in-depth thermal response of TACOT(Theoretical Ablative Composite for Open Testing), a charring ablator, resolving pyrolysis and pyrolysis-gas transport together with the surface energy and mass balances under equilibrium or finite-rate ablation. The framework is applied to the 2016 ExoMars Schiaparelli capsule under 2018 global dust storm conditions, with the dust environment constructed from Mars Climate Sounder opacity profiles following Palmer et al. [6] and an effective particle radius of 4.0 μm . The particle-collision heat flux contributes only marginally to the surface heat flux and thermochemical ablation compared with the material-coupling effect. Mechanical recession, however, is strongly sensitive to the dust environment: the 2018 storm yields approximately 9.3 times greater stagnation-point recession than the 2007 storm [7], exceeding the thermochemical ablation depth for the present trajectory segment. These results indicate that dust-induced mechanical erosion can measurably contribute to TPS degradation under severe dust storm conditions.

Keywords: dusty flows, Martian entry, thermal protection systems, multi-physics coupling, mechanical erosion

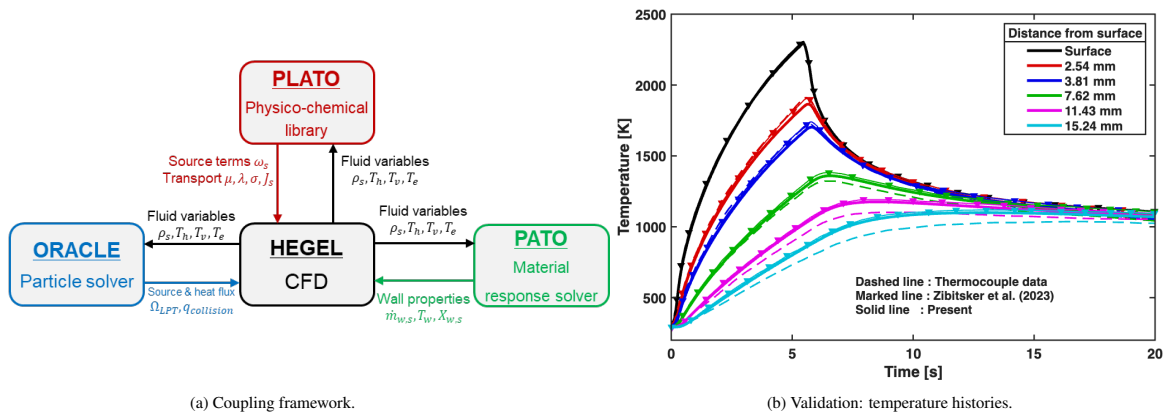


Figure 1: Multi-physics coupling framework and validation of the CFD–material response coupling against an arc-jet graphite ablation case [4].

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A Computational Thermo-Chemo-Poro-Mechanical Model of Pyrolyzing Ablative Thermal Protection Systems

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Abstract

Pyrolysis gases are central to the performance of ablative thermal protection systems (TPS), but when gas generation outpaces transport through the pore network, pressure accumulates in the pores and loads the solid skeleton. NASA attributed the char loss observed on the Artemis I Orion heat shield to this mechanism, reporting that gases retained inside the material allowed pressure to build and cracks to form [1]. Much emphasis has been placed on modeling the thermal and chemical response, while the mechanical loads exerted by the entrapped gas have received comparatively less attention. Notable exceptions are the models of Sullivan and Salamon [2] and Wu and Katsube [3, 4], which used the restrained thermal growth and free thermal expansion tests of FM5055 carbon phenolic as benchmarks and established the central role of pore pressure in the measured stress response.

We present a fully coupled thermo-chemo-poro-mechanical finite element framework for pyrolyzing ablators, derived from the mixture theory of chemically reacting porous media. The formulation combines a transient energy balance with endothermic decomposition and gas-enthalpy convection, multi-reaction Arrhenius pyrolysis kinetics, Darcy transport of the generated gas through the evolving pore network, and quasi-static equilibrium of a transversely isotropic poroelastic skeleton subject to thermal expansion, charring shrinkage, thermal softening, and pore-pressure loading. A staggered scheme couples the thermochemical and mechanical solves on unstructured two- and three-dimensional meshes.

We evaluate the coupled model against the benchmark tests. The restrained thermal growth tests show a two-peak evolution of the stress: thermal expansion against the stiff virgin skeleton produces the first compressive peak, thermal softening lowers the observed stress, pore-pressure loading on the softened material produces the second peak, and finally the pressure gets relieved as the gas is able to escape through the higher permeability char. The model is able to reproduce the measured stress response as shown in Fig. 1. The same parameters recover the non-monotonic strain of the free expansion test without recalibration. A permeability study on an iso-q geometry then quantifies the competition between gas transport and pressure buildup. Restricting the permeability confines the gas to the decomposing layer, substantially raising the peak pore pressure and the peak von Mises stress while relocating the stress concentration. These results identify permeability as a controlling parameter for pressure-driven damage in ablative TPS and motivate its careful characterization.

Keywords: pyrolysis, poroelasticity, pore pressure, permeability, stresses, thermal protection systems

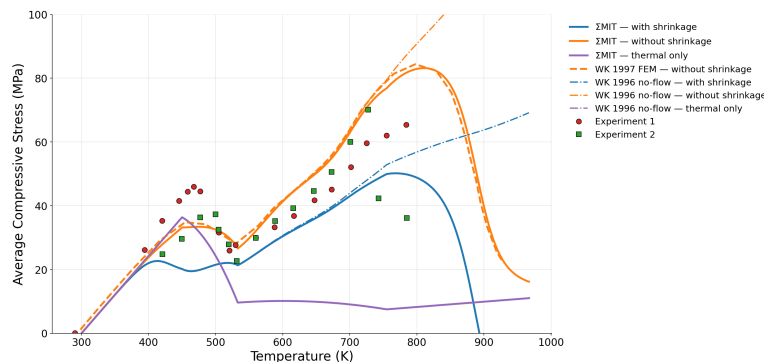


Figure 1: Restrained thermal growth test of FM5055 carbon phenolic: average constrained across-ply stress versus temperature. The present framework (Σ MIT) is compared against the predictions of Wu and Katsube [3, 4] and the experimental data reported by Sullivan and Salamon [2].

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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, 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 CFD model of the HVOF flame has been developed using Ansys Fluent with validation data provided by Johns Hopkins University Applied Physics Laboratory (APL) in the form of stagnation pressure and cold-wall heat flux measurements, shown in Fig. 1. Using a single-stage complete propane combustion mechanism, the simulation predicts stagnation pressure values to within 0.268psi of the measurements and cold-wall stagnation heat flux values to within an estimated measurement 90% confidence interval.

The CFD simulation is being coupled with Kentucky Aerothermodynamics and Thermal-response System (KATS), a thermochemical non-equilibrium flow solver developed by University of Kentucky [1], to perform a conjugate heat transfer simulation, with validation data provided by APL. The two-way coupling will be accomplished using precice [2], an open-source coupling library capable of bridging partitioned multi-physics simulations.

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

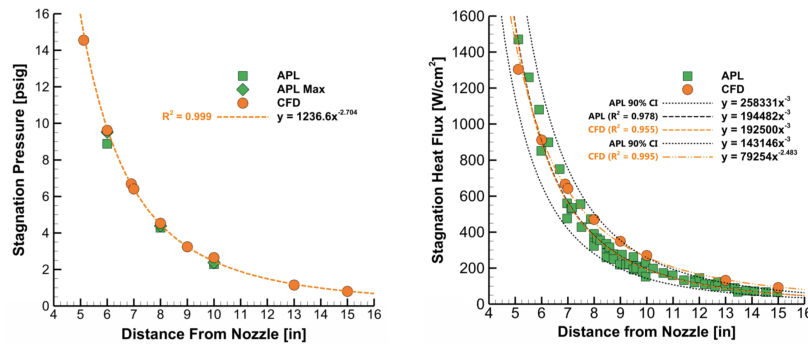


Figure 1: Flame stagnation pressure and cold-wall heat flux

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Reduced-Order Modeling of a One-Dimensional Charring Ablator Using Coupled Thermal-Decomposition Dynamics

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Abstract

Ablative thermal protection systems (TPS) are widely used in extreme heating environments due to their ability to absorb energy through material decomposition, char formation, and surface recession [1]. High-fidelity material response models for charring ablators involve coupled thermal transport, material decomposition, pyrolysis gas transport, and surface chemistry, resulting in significant computational cost for repeated simulations such as design optimization, uncertainty quantification, and real-time prediction [2, 3]. This work investigates a simplified reduced-order modeling framework for predicting the transient response of a one-dimensional charring ablator.

A coupled thermal-decomposition model is developed based on a transient heat conduction equation and a single-step Arrhenius decomposition model representing the transformation of virgin material into a charred state. The decomposition variable provides a measure of material evolution and is used to update effective thermophysical properties, including density, thermal conductivity, and heat capacity. Surface recession is incorporated through a moving-boundary formulation using an Arbitrary Lagrangian-Eulerian (ALE) framework. The resulting high-fidelity simulations capture the coupled evolution of temperature, material degradation, and ablative recession under prescribed heating conditions.

Reduced-order models based on Proper Orthogonal Decomposition (POD) and Dynamic Mode Decomposition (DMD) are developed from high-fidelity simulation data to efficiently approximate the transient ablation response [4, 5]. The effects of heating conditions, decomposition kinetics, and material evolution on reduced-order model accuracy and predictive capability are investigated. The results demonstrate the ability of data-driven reduced-order methods to reproduce the dominant thermal and material dynamics of ablative systems while substantially reducing computational cost. The proposed framework provides a foundation for extending reduced-order modeling approaches toward more complex charring ablators incorporating multiple decomposition reactions, pyrolysis gas transport, and detailed surface chemistry.

Keywords: charring ablators, dynamic model decomposition, reduced-order models

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A Computational Framework for Heterogeneous Oxidation and Fracture in Ultra-High Temperature Ceramics

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Abstract

Ultra-high temperature ceramics (UHTCs) are attractive materials for next-generation thermal protection systems because of their exceptional properties, including high thermal conductivity and strength. However, their structural integrity can be compromised by oxidation, which induces swelling, stress development, and fracture [1]. In these typically polycrystalline materials, these coupled degradation processes can be accelerated by the presence of microstructural short-circuit pathways, such as grain boundaries and intergranular cracks [2]. While these mechanisms have long been recognized, computational models capable of resolving such heterogeneous phenomena remain limited. We present a general framework for modeling coupled chemomechanical phenomena involving both interfacial and bulk response. The approach is based on the discontinuous Galerkin finite element formulation, which enables treatment of coupled interface/bulk mass transport, integration of cohesive fracture models, and modeling of accelerated diffusion due to crack formation. The framework is applied to mesoscale modeling of reaction and diffusion in polycrystalline UHTCs, capturing heterogeneous transport of reactants and products, oxidation-driven swelling, and damage evolution. Grain boundaries are represented as embedded interfaces that support both interfacial transport and separation. We verify the framework against analytical results regarding grain boundary diffusion in a bicrystal [3] and heterogeneous transport in general polycrystals. Finally, it is specialized to zirconium carbide (ZrC), a UHTC of particular interest [2, 4], and applied to polycrystalline microstructures to understand the mechanisms driving the experimentally observed oxidation-driven swelling and fracture in ZrC polycrystals.

Keywords: continuum modeling, micromechanics, oxidation, grain boundary diffusion, zirconium carbide

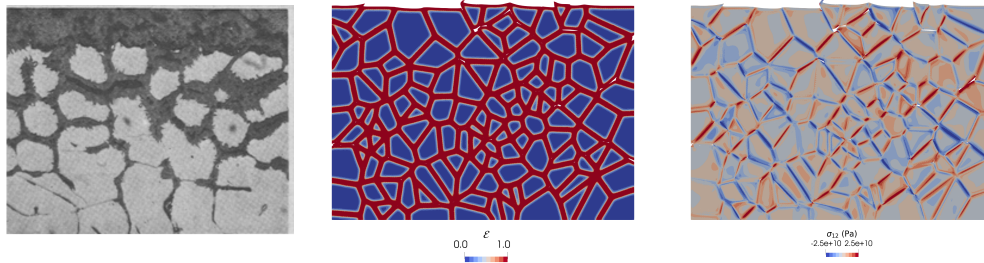


Figure 1: Experimental observations and corresponding simulations of oxidation-induced degradation in ZrC. (Left) Pronounced grain boundary oxidation in a polycrystalline ZrC microstructure [1]. (Middle) Simulated extent of reaction in a polycrystalline ZrC microstructure. (Right) Simulated shear stress field associated with heterogeneous oxidation-induced swelling along grain boundaries.

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Uncertainty-Aware Air Carbon Ablation Model from Molecular Beam Data

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Abstract

The strong shock produced ahead of a vehicle traveling through the atmosphere at hypersonic speeds creates reactive gas species that impinge on and degrade the vehicle's surface through complex thermochemical processes. Gas-surface interaction (GSI) models, which are designed to predict this phenomena, are often composed of a system of chemical reactions that characterize the interactions between the dominant gas species in the flow and the surface of the vehicle. The Air Carbon Ablation (ACA) model is a state-of-the-art GSI model that contains 20 reactions which describe the interactions between dissociated air species and a carbon-based Thermal Protection System (TPS). The ACA model contains several free parameters within its reaction mechanisms that are challenging to identify unequivocally from available experiments, which is a major limitation in its implementation due to the resulting difficulty in defining the uncertainty in its predictions.

This limitation of the ACA model leads us to deploy Bayesian inference techniques to determine the free parameters as a high-dimensional probability distribution instead of individual scalar values. Bayesian inference allows us to learn the distribution of the parameters with respect to data from molecular beam experiments, which provide key insight into the probability that reactions occurring on a surface create specific gas products. The posterior parameter distribution determined via Bayesian inference enables uncertainty to be propagated forward through the ACA model, yielding predictions with confidence intervals and other related uncertainty metrics that are essential to TPS design. One drawback of Bayesian inference is that it is accomplished by building a correlated, finite-length chain of parameter samples via a Markov Chain Monte Carlo (MCMC) algorithm, which inhibits certain uncertainty quantification (UQ) tasks which may require a large number of uncorrelated samples. We address this by constructing a generative sampling model via a triangular transport map that can produce any number of unique, independent samples from the posterior distribution. This generative model allows us to carry out any downstream UQ task.

Analysis of the posterior distribution of the parameters and the posterior predictive of the gas products across a wide temperature range indicates that molecular beam data is significantly informative for a large quantity of individual parameters. Additionally, simulations run at conditions observed in inductively-coupled plasma facilities reveal that the stochastic ACA model predicts the general trends observed in several experiments. Finally, a sensitivity analysis shows a clear transition in dominant uncertainty modes at a temperature just past the highest temperature data point reported in the molecular beam experiments, indicating that alternative sources of experimental data should be considered to further refine the ACA model and to maximize the information gained through subsequent Bayesian inference analyses.

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

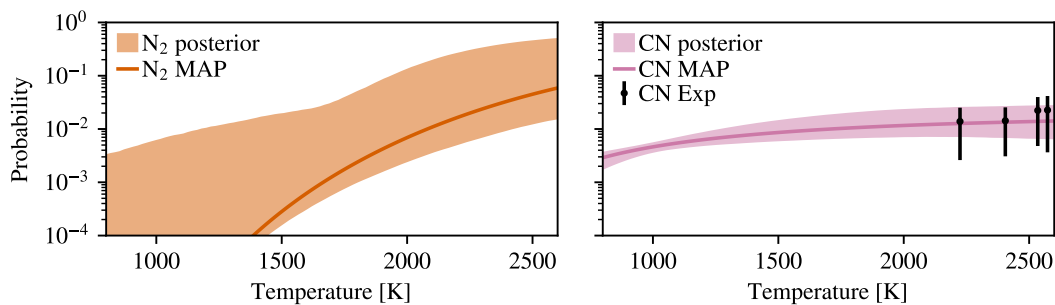


Figure 1: Posterior predictive uncertainty in the ACA model at 1600 Pa for select nitrogen species (CN data from del Val et al. [1])

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A Scalable Framework for Hypersonic Aero-Thermo-Chemo-Mechanical Simulations of Thermal Protection Systems

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Abstract

High-fidelity simulation of hypersonic fluid–solid interaction requires the tight coupling of computational fluid dynamics and solid mechanics solvers, both of which must remain efficient on massively parallel computing platforms. This work presents a scalable coupling framework between two high-order discontinuous Galerkin (DG) multiphysics libraries, Exasim [1] and Σ MIT [2], for aero-thermo-chemo-mechanical simulations of hypersonic vehicles and thermal protection systems (TPS) [3]. The framework couples independently parallelized solvers through a lightweight MPI communication layer, using geometric bounding-box searches to build distributed transfer operators between the non-conforming interface meshes, thereby avoiding a partitioned Dirichlet–Neumann coupling strategy is used to transfer fluxes and state quantities across the interface to ensure enforcement of the interface conditions. An Aitken relaxation algorithm is employed for stability reasons and to accelerate convergence. The coupled framework is verified on a transient heat transfer problem with a known analytical solution and is demonstrated in a simulation of a pyrolyzing Iso-Q PICA specimen under hypersonic flight conditions, where aerodynamic heating drives thermochemical decomposition in the material and gas injection into the boundary layer.

Keywords: thermal protection systems, multiphysics coupling, Discontinuous Galerkin, parallel scalability

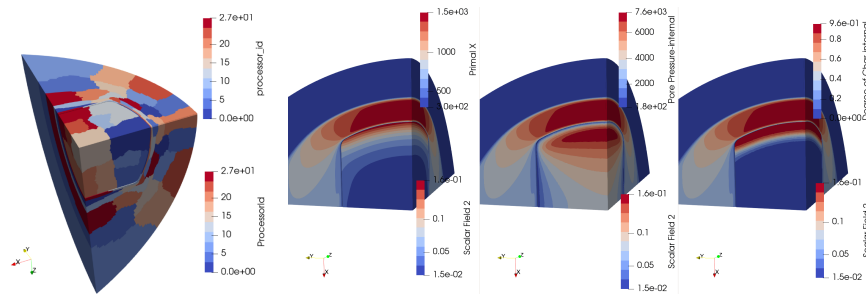


Figure 1: Left: Non-conforming interface meshes and non-matching MPI partitions of the fluid and solid subdomains. Right: Simulation of a pyrolyzing Iso-Q specimen of PICA under hypersonic flight conditions (Mach 7, 50 km altitude), showing the temperature field in the flow and the thermo-chemical degradation and pressure build-up in the material.

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ARCTRON: A Rapid Experimental Proving Ground for TPS Experiments and Arcjet Technology Development

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Abstract

Innovation in high-enthalpy facilities is fundamentally limited by the cost and risk of experimentation. New concepts for plasma control, diagnostics, facility components, and plasma-material interaction often require repeated iterations that are impractical to perform in production arcjets. As a result, promising ideas may remain unexplored or reach operational facilities only after significant development effort.

ARCTRON is being developed as a rapid experimental proving ground where new ideas in plasma science, arcjet engineering, diagnostics, and material response can be conceived, tested, and quantitatively evaluated before transition to large-scale facilities. The platform combines radio-frequency (RF) and DC arc plasma generation, externally applied magnetic fields, configurable gas composition, reduced-pressure operation, laser heating, electrical biasing, and modular diagnostic access. These capabilities permit the plasma source, applied forcing, test article, and measurement configuration to be modified independently, allowing individual physical mechanisms to be isolated more readily than in a traditional test environment.

One class of investigations addresses fundamental plasma-surface interaction physics. Conventional material tests often expose a specimen simultaneously to convective heating, reactive species, pressure, shear, radiation, and surface-current effects. The resulting material response may be measured accurately, while the contribution of each mechanism remains difficult to identify. ARCTRON is designed to vary these effects selectively. Plasma chemistry can be changed independently through configurable gas mixtures; magnetic fields and electrical biasing can modify charged-particle transport; laser heating can provide a non-plasma thermal input; and pressure, flow, and discharge mode can be varied over a broad operating space. This enables controlled tests of hypotheses involving surface catalyticity, reactive-species transport, plasma-assisted oxidation, electromagnetic effects, shear, and the relative contributions of thermal and chemical loading.

A second class of investigations enabled by this approach concerns the engineering of high-enthalpy facilities themselves. Arc-heated facilities are limited by electrode erosion, unstable arc attachment, localized heating, and damage to nozzles and other plasma-facing components. ARCTRON provides a lower-cost environment for testing concepts intended to mitigate these limitations. Candidate investigations include the use of applied magnetic fields to alter current paths and reduce plasma interaction with nozzle walls, $\mathbf{E} \times \mathbf{B}$ forcing to introduce controlled plasma rotation, magnetic or geometric approaches for distributing arc attachment, and alternative electrode or discharge configurations intended to reduce erosion and improve stability. Because the platform is reconfigurable, these concepts can be evaluated through repeated design–build–test cycles before they are considered for implementation in operational facilities.

The platform also supports the development and validation of diagnostics that may be difficult to introduce initially into a large arcjet. Current and planned measurements include spatially resolved optical emission spectroscopy, electrostatic probes, fast imaging, pyrometry, calorimetry, laser-induced fluorescence, and absorption spectroscopy. These diagnostics are intended not merely to document a nominal operating condition, but to constrain the local plasma state and its relationship to component or material response. The modular facility geometry allows diagnostic concepts to be tested, calibrated, and compared under repeatable conditions before deployment in more demanding environments.

ARCTRON is also supported by an integrated software suite. Automated control and data acquisition allow discharge parameters, gas composition, magnetic fields, diagnostic timing, and test configuration to be recorded as part of each experiment (STARDAC - Software for Testing, Analysis, Research Data, and Control). The Backend for Experiment Analysis, Storage, and Traceability (BEAST) [1] is a database that provides the infrastructure needed to

associate heterogeneous measurements with facility configuration, specimen identity, calibration state, geometry, and analysis provenance. This backend is particularly important for exploratory campaigns, in which many related configurations may be tested and the value of an individual experiment depends on its connection to earlier and subsequent iterations. Complementary analysis capabilities, including computer-vision-based transient response measurements (arcjetCV), three-dimensional surface reconstruction (STARSCAN), and model-based Bayesian inference (SHIELD), and tomography data analysis (TOMATO, PuMA) can be incorporated when required by a specific hypothesis without becoming the focus of every campaign.

The central objective of ARCTRON is therefore not to maximize heat flux or reproduce a complete flight environment. Its purpose is to reduce the cost and time required to ask consequential questions about plasma behavior, plasma-facing materials, diagnostics, and arcjet technology. By providing a controlled environment for rapid reconfiguration, mechanism isolation, quantitative measurement, and iterative engineering, ARCTRON can help mature concepts that would otherwise remain too speculative or too risky for evaluation in production facilities. The resulting knowledge can then guide the design of material models, focus test objectives in larger arcjets, reduce facility-development risk, and improve the physical basis of high-enthalpy ground testing.

This work will present the ARCTRON architecture, operating modes, diagnostic suite, and digital experimental workflow. Initial experimental results from the first integrated operation of the facility will be presented, including flow characterization, power limitations, and deployment of the initial diagnostic suite. Ongoing development efforts aimed at catalytic characterization, magnetic plasma control, and advanced optical diagnostics will also be discussed, illustrating how the platform supports rapid iteration from concept to experiment.

Keywords: plasma-material interaction, arcjet, high-enthalpy testing, magnetohydrodynamics, facility development, experimental diagnostics

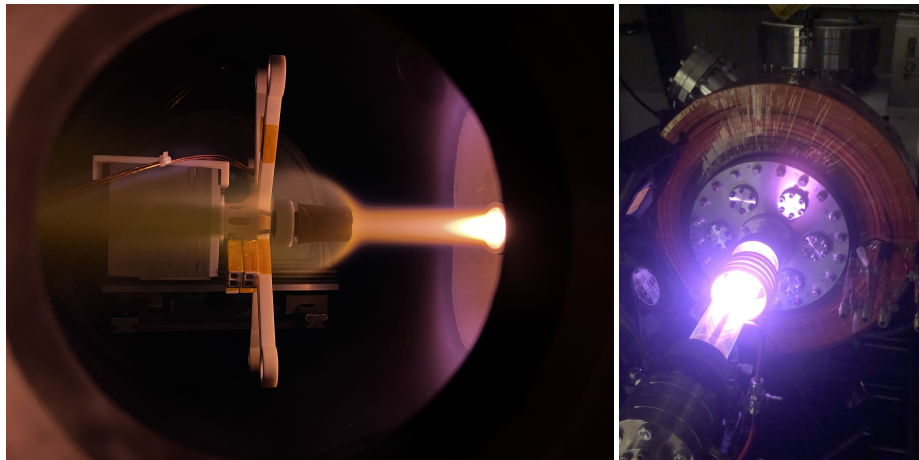


Figure 1: ARCTRON images (left) ARCTRON test of cork sample held in 6-position sting arm (2D axial and rotation motion axes) (right) image showing plasma generation external to the chamber

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Stochastic Network Modeling of Progressive Failure in a Fiber-Based Material

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Abstract

Predicting the mechanical response of fibrous ablators such as PICA and its FiberForm precursor requires capturing failure at the fiber scale, where localized stress concentrations and damage events determine macroscopic behavior. Most continuum models homogenize these features. We present a stochastic 3D finite element framework—with explicit fiber and binder phases—designed to generate full stress-strain curves for a PICA representative volume element (RVE). We further demonstrate every damage event logged by mechanism: tensile and compressive fiber failures, Euler buckling, bending failures, and cases in which fibers stop transmitting load because their adhesive junctions have broken. Fiber geometry is stochastically generated at measured volume fractions. The orientation distributions reflect FiberForm’s transversely isotropic microstructure and capture its network localization behavior. A micro-scale COMSOL model characterizes the adhesive binder at each crosslink to supply the torsional spring stiffnesses for the stochastic network. Binder debonding is governed by a cohesive zone model whose traction-separation law is computed using reactive molecular dynamics (MD) simulations of Mode I opening and Mode II sliding failure. Hence, MD simulations of an amorphous carbon binder on a graphite fiber basal plane are directly used to obtain normal and shear interface strengths. A progressive failure loop advances the network through crosslink debonding and fiber failure towards complete fracture. Our results can be compared with experimental stress-strain curves for uniaxial tension and compression of PICA, and we are able to observe the role of individual mechanisms in the progressive failure of the material.

Keywords: PICA, fiber-binder interface, cohesive zone model, molecular dynamics, RVE

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Atomic oxygen measurements via coherent anti-Stokes Raman Scattering: a new path for study of recombination physics

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Abstract

During peak heating, post-shock ablation environments are characterized by dissociated air, where atomic oxygen chemistry is a dominant mechanism impacting material recession and surface heat flux. Recombination of atomic oxygen to molecular O_2 in the gas phase or by surface catalysis remains an open question. Spatially precise measurement of atomic oxygen can be provided by laser-induced fluorescence [1], which does not offer simultaneous detection of recombined O_2 . Atomic oxygen has been observed alongside O_2 in Raman and coherent Raman (CARS) spectra [2], and Raman methods have potential for spatially resolved simultaneous measurement of T/O_2 with a single diagnostic tool [3]. Recent ultrashort-pulse fs/ps CARS measurements from the boundary layer of a cooled copper hemisphere embedded in an Ar/O_2 inductively coupled plasma torch will be discussed and are shown in Figure 1. The measurements can be performed in 1D line-imaging mode, where each row of the spectrogram in (a) may be fit to a spectroscopic model (b) for simultaneous T and O/O_2 ratio, providing a direct observation of oxygen recombination in the reacting boundary layer. Stagnation-region boundary layer profiles of temperature and O/O_2 ratio are shown in (c). These proof-of-concept measurements indicate superequilibrium levels of O atom within the near-wall region, with complete consumption of atomic oxygen at the copper surface. Measurement uncertainty is discussed and a path to insertion of oxygen atom CARS for experiments in Illinois Plasmatron X and Plasmatron I is provided.

Keywords: ablation, recombination, oxygen atom, laser diagnostics

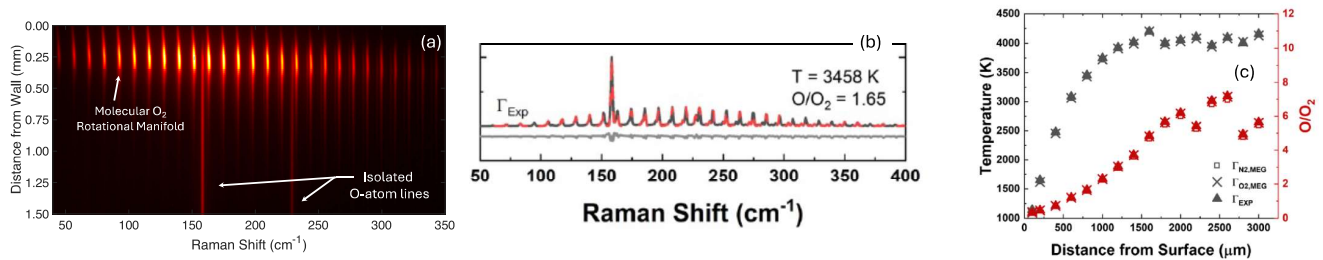


Figure 1: (a) One-dimensional CARS line-imaging spectrogram; (b) representative fit to a single-row spectrum for temperature and O/O_2 ratio in recombining boundary layer flow; (c) resulting boundary layer profiles

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July 15, 2026

Qualification in CO₂ of the TPS and the aerothermal instrumentation for the EXOMARS RFM mission

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Abstract

The future largest capsule heatshields ever done in Europe (featuring a 3.8 m diameter, designed, manufactured, and tested by ArianeGroup SAS [1] [3], will be launched in 2028 and will enter on Mars after a trip of several months. Build upon the post flight analysis of Schiaparelli [2], the thermo-ablative model of the Outgassed Norcoat® Liège (a phenolic resin impregnated cork matrix) has been enriched through new several plasma test campaigns in air but also in CO₂ (Fig. 1). These campaigns 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 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 the latest plasma torch performed in pure CO₂ plasma.

Keywords: ablation, TPS: thermal protection systems, Mars, Norcoat Liege



Figure 1: ESIMOUN (arc-jet heater) wedge specimen for the tile pattern and aerothermal instrumentation qualification campaign

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Investigations the influence of gas-surface reactions to compute RF Blackout in atmospheric entry

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Abstract

During the atmospheric reentry of Apollo 11, the spacecraft traveled at hypersonic speed through the upper atmosphere, leading to a communication blackout with Houston that lasted more than four minutes. Despite decades of research, the mechanisms governing radio-frequency (RF) blackout remain only partially understood, and current predictive models still lack accuracy.

Under hypersonic reentry conditions, a strong bow shock forms ahead of the vehicle, compressing and heating the surrounding gas. The resulting high temperatures trigger numerous physicochemical processes, including molecular dissociation, ionization and electronic excitation. At the same time, intense heat transfer to the thermal protection system raises the surface temperature, potentially causing material ablation and catalytic surface reactions. The gas-surface interactions, including catalytic recombination [1, 2], oxidation, sublimation and nitridation [3], alter the chemical composition of the boundary, influencing electron production near the wall. The resulting weakly ionized plasma surrounding the vehicle can absorb or reflect electromagnetic waves, leading to RF signal attenuation and, in severe cases, complete communication blackout, as illustrated in Fig. 1.

This work aims to improve the physical models implemented in an in-house computational framework to accurately predict electron density under atmospheric reentry conditions, with particular emphasis on the near-wall region where gas-surface interactions play a critical role. The study investigates a multi-species CFD model coupled with surface chemistry models accounting for catalycity, oxidation, sublimation and nitridation, while assessing the influence of diffusion processes, such as SCEBD (Self-Consistent Effective Binary Diffusion) [4] or multicomponent [5], on plasma formation. The resulting flow-field predictions are then coupled with an in-house electromagnetic solver to quantify RF signal attenuation along the line of sight (LOS). The results highlight the need to take account of surface reactions to accurately predict electron density within the plasma layer, as shown in Fig. 2. Finally, the complete computational framework is validated against experimental measurements from the RAMC-II flight experiment [6], demonstrating its capability to predict communication blackout under realistic reentry conditions.

Keywords: Hypersonics, Plasma, Atmospheric Reentry, CFD, Diffusion, RF Blackout, Gas-Surface Interactions

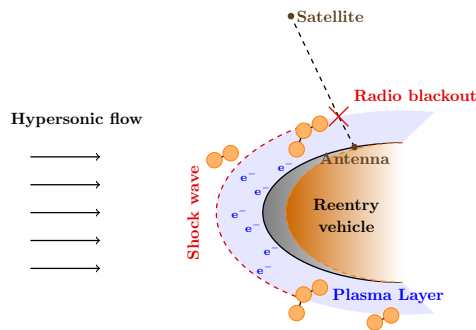


Figure 1: Scheme of RF blackout.

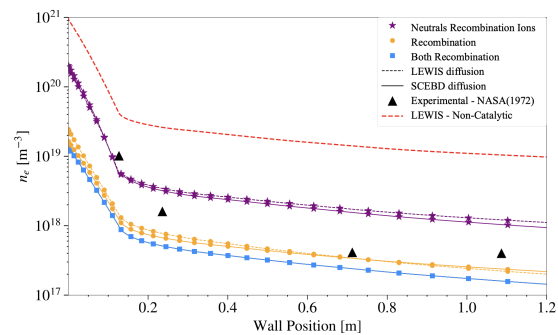


Figure 2: Influence of catalycity on electron density along the vehicle wall at 61 km.

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Analyzing the impact of GSI models on Fluid-Radiation Coupled Simulations

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Abstract

During high-speed Earth entry, radiative heating becomes a dominant contribution to the wall heat load [1], and it is two-way coupled with surface ablation: ablation products injected into the boundary layer both emit and absorb radiation, while radiation drives the wall temperature and hence the ablation rate itself [2]. This work quantifies this coupling with coupled CFD–radiation simulations of a 60° sphere-cone capsule entering Earth’s atmosphere at 10 and 15 km/s, using a framework composed of the flow solver HEGEL [3], the thermochemical library PLATO [4], and the radiation solver MURP [5]. The finite rate air–carbon ablation model [6] is compared with a fully catalytic, ablation-free wall, and extended with carbon sublimation and a steady-state pyrolysis closure that injects hydrogen-bearing pyrolysis gas into the boundary layer. Results show that the effect of ablation on radiative heating reverses with velocity: at 10 km/s, emission from C and CN raises the wall radiative flux (+27%), whereas at 15 km/s, boundary-layer absorption by carbon species outweighs the added emission and lowers it (–24%, Fig. 1).

Keywords: ablation, radiation, gas–surface interaction, hypersonic entry

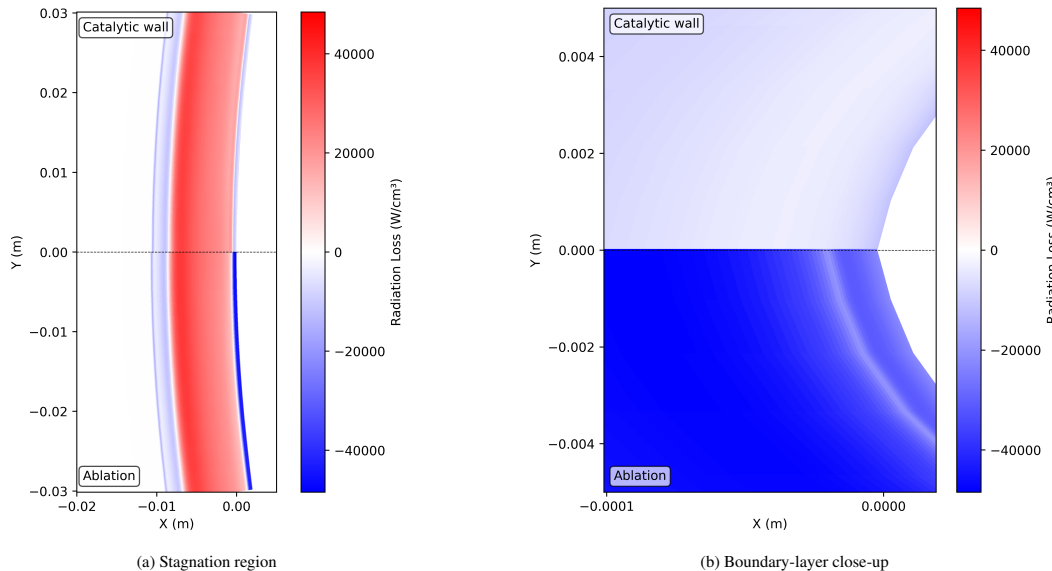


Figure 1: Radiative source term at 15 km/s: fully catalytic wall (top) and GSI wall (bottom). Emission (red) peaks in the equilibrium core behind the shock, while carbon ablation products cause the strong absorption layer (blue) next to the surface.

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Time-resolved Micro-CT of Methane Coking in Carbon Fiber Preform

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Abstract

During atmospheric entry, the pyrolyzing matrix in carbon-phenolic ablators releases hydrocarbon gases into the porous char. As these products pass through strong gradients, heterogeneous reactions can deposit pyrolytic carbon on the carbon fibers and the porous charred structure [1–3]. This coking process may alter permeability, pore morphology, and effective thermo-physical properties; however, its progression inside the material is difficult to observe using conventional characterization methods. *In situ* synchrotron micro-computed tomography (micro-CT) with time resolution provides a means of examining evolving carbon-fiber microstructures at high temperatures [4]. This study uses synchrotron micro-CT to investigate carbon deposition within FiberForm, the porous preform of NASA's Phenolic Impregnated Carbon Ablator (PICA). Experiments were performed at Lawrence Berkeley National Laboratory's Advanced Light Source tomography beamline 8.3.2 using a custom reactor that enables controlled gas flow, chamber pressure, and infrared laser heating of the sample surface to temperatures exceeding 2400°C. Methane was selected as the reactant because of its dominance in species populations observed in PICA pyrolysis experiments [5]. Heating and methane exposure were interrupted at regular intervals to image the evolving internal microstructure. Eight experiments were conducted at various pressures, temperatures and mass flow rates, with six full-volume scans collected from the virgin state through nominally 5 minutes of cumulative coking. Ongoing three-dimensional segmentation and post-test characterization aim to quantify the spatial and temporal development of deposited carbon and its influence on the FiberForm pore structure under conditions relevant to atmospheric entry.

Keywords: FiberForm, Coking, Carbon Deposition, Micro-CT, Pyrolysis, Laser Heating

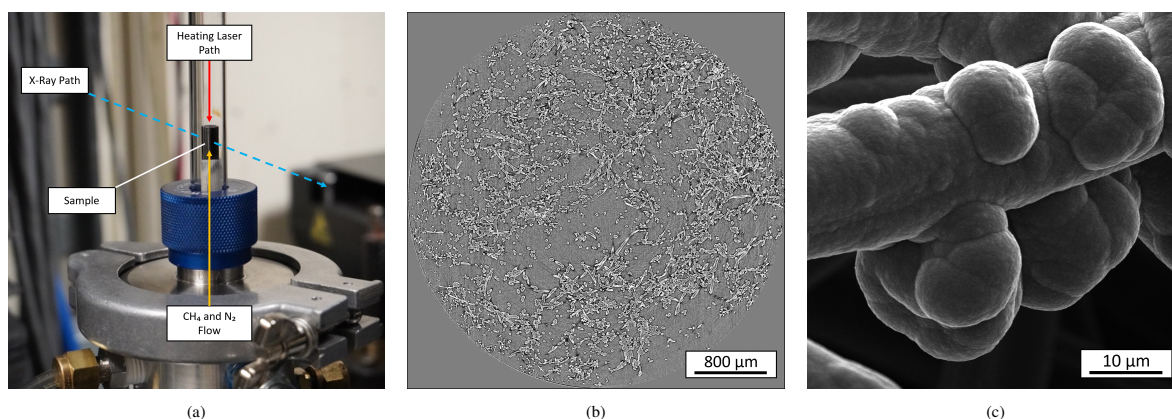


Figure 1: (a) FiberForm sample seated within a vitreous carbon tube inside the custom reactor. The X-ray beam path, laser-heating path, and direction of gas flow are illustrated. (b) Transverse micro-CT slice through the FiberForm sample following 5 min of cumulative methane exposure. (c) Post-test SEM image of FiberForm fiber showing coked-carbon deposition on the fiber surface.

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Few-shot multistage phase classification in CT scans of carbon-carbon composites

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Abstract

Characterizing complex carbon-carbon (C-C) composite materials from X-ray computed tomography (CT) scans requires accurate segmentation of constituent phases, such as fibers, matrix, and voids. While vision foundation models like Meta’s Segment Anything Model (SAM) excel at rapid object-level mask generation, they do not inherently provide dense, non-overlapping semantic classification, nor do they capture the complex spatial and physical interactions between composite phases. To bridge this gap, we introduce a few-shot, multistage machine learning workflow. In this approach, SAM’s automatic mask generation is first combined with superpixel gap-filling to yield a complete, boundary-preserving partition of the scan. A Stage-1 classifier then leverages local microstructural features—including radiomics, void morphology, and localized fiber orientation—to assign baseline phase probabilities based on minimal user-annotated data. Because local texture alone can be ambiguous in low-contrast C-C composites, a Stage-2 meta-classifier is subsequently applied. This refinement stage incorporates physics-informed spatial and geometric contexts, such as nesting depth, adjacent neighbor phase relationship, and directional phase continuity—to resolve conflicts and enforce global consistency. By combining foundation model object proposals with hierarchical spatial relational priors, this few-shot multistage workflow resolves local ambiguities and achieves high accuracy, physics-aware phase classification without requiring large annotated training datasets.

Keywords: Few-shot learning, phase classification, vision foundation model, CT scan, carbon-carbon materials

Stochastic reconstruction of ablating material properties for uncertainty propagation in material response simulations

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Abstract

Material response models are used to assess reliability using variances in the bond-line temperature predictions based on uncertainties in the trajectory, aerothermal environment, and material properties. A key deficiency in the current approach is that input uncertainties are often subjective and are not rigorously linked to the arc-jet test data used to develop the TPS material model. Although materials such as PICA are well understood, future missions may require more novel materials such as 3MDCP where unknown uncertainties have real consequences on the ability to assess reliability.

Bayesian inference mathematically defines a connection between prior knowledge, model uncertainty, and observation. [1] coupled a Karhunen–Loève expansion with Gaussian-process (KLE-GP) regression to construct a reduced-order surrogate for the time-dependent in-depth temperature response, thus making Bayesian inference of the uncertain model parameters computationally tractable. In this work, we extend the parameterization of uncertain material properties to allow the magnitude of their uncertainty to vary with temperature and degree of decomposition. Additionally, we expand the set of uncertain model parameters to include the Arrhenius kinetic parameters governing material decomposition and demonstrate that these parameters can be calibrated against thermogravimetric analysis (TGA) data and then incorporated into the development of material models using arc-jet test data. Finally, we demonstrate newly developed workflows that propagate the resulting posterior uncertainty through a TPS sizing problem, illustrating how uncertainty can be treated consistently in engineering design and analysis.

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URL <https://doi.org/10.2514/6.2025-1427>

Multi-species Implementation in Material Response Code

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Abstract

Recently, experiments were performed [1] that made it possible to include pyrolysis species generation in material response codes. Based on that, the Arrhenius parameters of the reactions and the stoichiometric coefficients for the species are calculated using an in-house Python script. The Kentucky Aerothermodynamics and Thermal-response System (KATS) material response (MR) code is then updated to account for the generation of multi-species pyrolysis gases. The reactions between the pyrolysis species are unknown; therefore, Mutation++ is employed to determine the equilibrium composition of gases generated during decomposition, providing a physical representation treatment of pyrolysis chemistry. A 1-D test case is prepared with a linearly increasing heating rate with reactions. The mass fraction in the case with no reaction is given in 1(a), demonstrating successful implementation of multi-species generation. The case with the reactions is given in Fig. 1(b), showing that most of the species are consumed and that there are two produced species. A follow-on case, including full surface mass and energy balances, will evaluate the model under realistic ablation conditions.

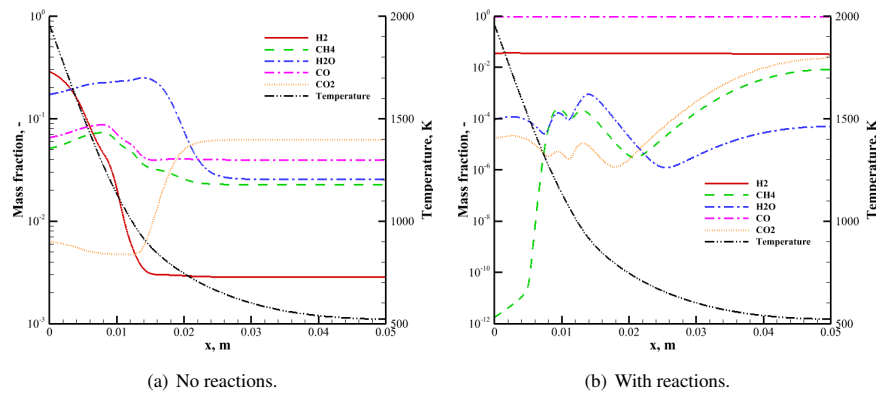


Figure 1: The mass fraction of the major species.

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

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Investigations of High-Temperature Oxygen-Carbon Ablation by Molecular Beam-Surface Scattering

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Abstract

This presentation will focus on the findings of many molecular beam-surface scattering experiments to gain an understanding of the high temperature (1000 – 2000 K) atomic-oxygen-induced ablation of model carbon materials. Earlier molecular beam data were used as the basis of an air-carbon ablation model (generally referred to as the “ACA model”), but refinement of this model was needed to make it more applicable to a variety of carbon morphologies. Thus, new molecular beam experiments have been conducted to expand the range of carbon materials studied, and the new data have been provided to inform an update of the ACA model in the group of Prof. Tom Schwartzentruber at the University of Minnesota.

The new experiments were performed with pulsed molecular beams of O atoms. The reactive scattering dynamics of O on various carbon surfaces – vitreous carbon (revisited), HOPG, isostatically-molded graphite (IMG), and a 3D carbon-carbon composite (C/C) – suggest that the oxidation mechanisms on all sp^2 types of carbon are similar but that the morphology of the surface region strongly influences the relative importance of the individual mechanisms. The relative probabilities of the observed gas-surface interactions, both reactive and non-reactive, were quantified as a function of surface temperature. Carbon surfaces that have lower density or more porosity tend to exhibit higher reactivity. In addition to reacting with carbon to produce CO_2 (minor product) and CO (major product), unreacted O atoms may scatter through thermal and non-thermal processes, and, with sufficiently high incident O-atom flux, O-O recombination on the surface to produce O_2 may occur with an efficiency that is somewhat lower than that to produce CO. Furthermore, O atoms may be retained through adsorption on the surface or absorption into the bulk, leading to slow production of CO on a timescale of tens of microseconds to hundreds of milliseconds. The slow processes through which CO is formed and released from the surface may account for as much as half the CO that is produced at lower temperatures, whereas the slow production of CO becomes negligible at higher temperatures and all the CO is released within a few microseconds of O-atom impingement on the surface. Relative to vitreous carbon, IMG and C/C show broader temperature ranges over which slow thermal release of CO remains important. The molecular beam scattering results indicate the importance of microstructure in the temperature-dependent ablation rate of carbon by atomic oxygen. The results further show that slow CO production, on a timescale up to hundreds of milliseconds, should be considered in experiments and models where the finite rate of oxygen-carbon ablation may be important.

Multivelocity Formulation Discretized Using Combined Discontinuous Galerkin and Material Point Methods for Ablation Simulations

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Multivelocity formulation has been used in modeling multiphase flows. This formulation technique has been extended to study fluid-structures interactions. One of the distinguished features of this formulation method is that the material interaction conditions, such as no-penetration and traction continuity, can be satisfied automatically in a numerical calculation, if the material interface can be kept sharp. For this purpose, the material point method (MPM) is used to simulate the solid material. The Lagrangian material points are used to track the history and the domain occupied by the history-dependent solid. Variables, such as plastic strain, damage, orientations, of material can be carried by the material points. To calculate the flow field around the solid object, the discontinuous Galerkin method is used. The coupling of these methods, (i.e. of the coupling) of the fluid and solid will be discussed along with numerical examples.

Influence of Surface Recession on Transitional Fluid–Ablation Interactions over a Mach 8 Compression Ramp

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Abstract

Direct numerical simulations (DNS) are performed to investigate fluid–ablation interactions (FAI) and their influence on instability growth and boundary-layer transition over a 15° compression ramp at Mach 8. The configuration is motivated by wind-tunnel experiments exhibiting characteristic spanwise heating streaks near reattachment. These streaks are first reproduced over an inert ramp by introducing perturbations, informed by stability calculations, into the laminar base flow. The rigid surface is then replaced by camphor, a low-temperature ablator, to examine the coupled effects of heat transfer, mass blowing, and surface recession. Simulations are carried out with two separate computational frameworks, CHAMPS and INCA, which produce closely consistent predictions of wall heat transfer, ablation-induced blowing, and surface deformation. Numerical experiments further assess the influence of accelerated recession and increased perturbation amplitudes. While ablative blowing has an overall stabilizing influence, surface recession produces streamwise grooves that sustain disturbance growth and promote transition. These results demonstrate the importance of surface evolution in predictive simulations of transitional hypersonic flows over ablating materials.

Keywords: Fluid–ablation interaction, hypersonic transition, direct numerical simulation, surface recession, compression ramp

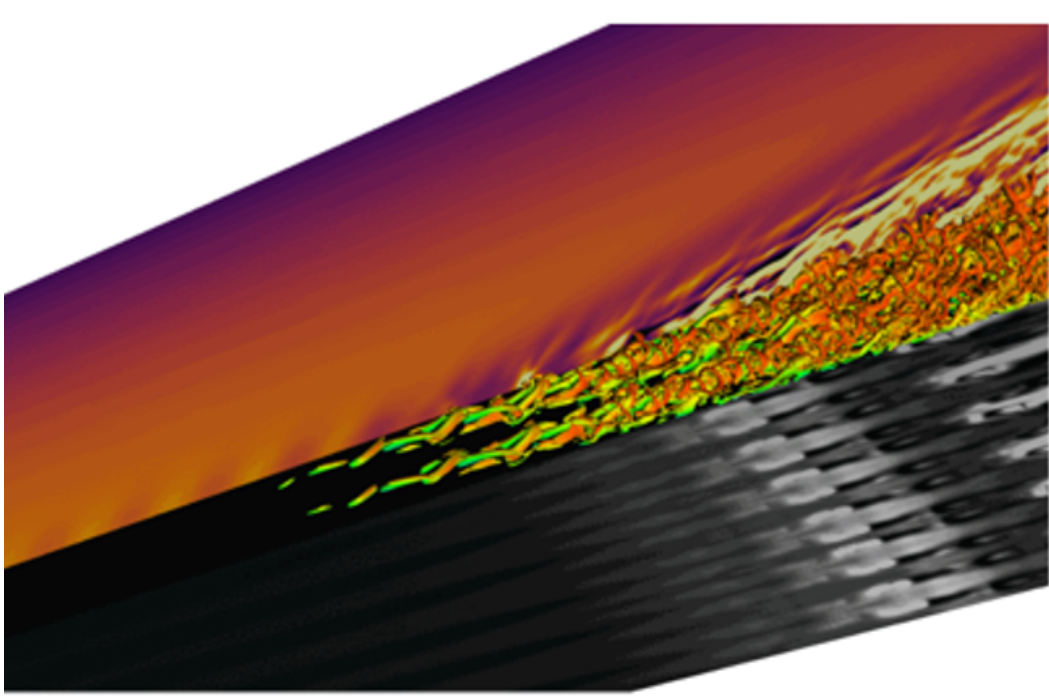


Figure 1: Oblique first-mode breakdown coupled to a B-prime ablation model. Surface contours show recession, the slice shows instantaneous pressure, and Q-criterion isosurfaces colored by streamwise velocity highlight vortical structures and strong nonlinear surface patterning.

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Characterization of the resin structure in PICA

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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. 1) 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, three volumes were captured with a cross-sectioning distance of 20 nm and a resolution of $4.27 \times 4.27 \times 20 \text{ nm}^3$. Manual segmentation of each cross-sections is impractical and prone to bias. Therefore, a 3D U-Net convolutional neural network and a Sensor3D model was developed to automate segmentation. The models were 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. 1. The Heterogeneous Effective Representative Multi-scale property Extraction Software multi-scale (HERMES) code was used to study 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

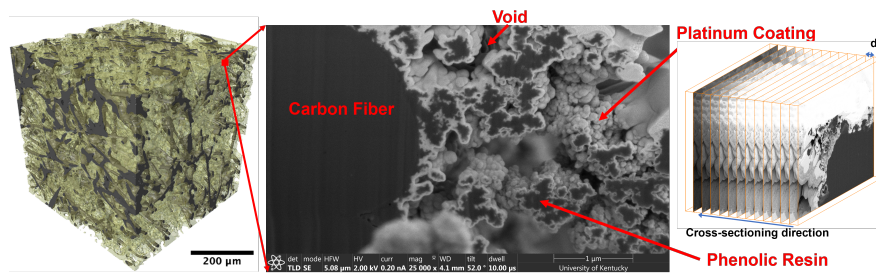


Figure 1: Multi-scale feature of the phenolic resin in PICA captures with XRCT and FIB-SEM. In the 3D volume rendering of PICA, light yellow is resin and dark gray are fibers.

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Modeling laser-based ablation of carbon materials

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Abstract

Laser heating methods offer a flow-free solution to ablating materials. With a laser-based heating technique, materials can be exposed to high heating conditions in low-pressure environments. In a rarefied air environment, ablation is solely driven by sublimation, allowing the phenomenon to be isolated and decoupled from oxidation. In March 2025, a campaign was conducted at the Aerospace Laboratory for Lasers, Electromagnetics, and Optics (ALLEMO) at Texas A&M University. The experiments heated material samples inside a vacuum chamber using a continuous-wave IPG laser [1]. This work presents the modeling of seven main experiments under three different conditions from the campaign [2]. The modeling is conducted with a multidimensional material response solver, the material response module of the Kentucky aerodynamic and thermal-response system (KATS-MR). The solver is coupled with a radiative solver to properly compute the re-radiative heat flux inside the craters. The temperature results and recession profile of the simulations are compared to the experimental data. The comparison for the low-power case is shown in Fig. 1. The comparison indicates the framework performs well at low-power conditions, but the discrepancy grows as laser power increases. This work discusses possible mechanisms and physical phenomena missing from the material response solver that can explain the discrepancy in results.

Keywords: Laser ablation, sublimation, material response, computational modeling.

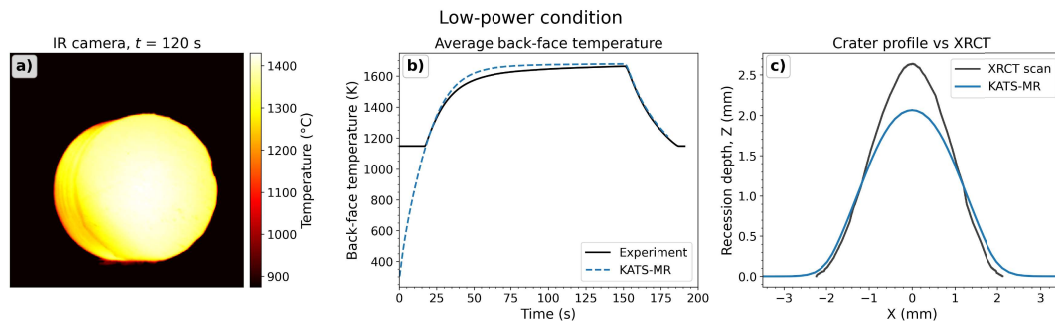


Figure 1: Modeling of low-power condition experiment. a) Frame of data captured from FLIR camera during the experiment. b) Average back-face temperature comparison between experimental data and material response simulation. c) Recession depth comparison between experimental data and material response simulation.

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Sublimation of carbon materials

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Abstract

In March 2025, an experimental campaign was conducted, where a 2 kW continuous wave laser was used to ablate various samples in a vacuum chamber. The goal of the campaign was to use the low-pressure, inert environment of the vacuum chamber to reduce the ablation process to sublimation, allowing the mechanisms to be studied isolated from oxidation. Three different materials were chosen for the experiments: FiberForm, graphite, and a 2D carbon/carbon (C/C) composite. A total of 52 experiments were performed, divided across seven main conditions. This work presents an overview of the campaign and the subsequent efforts to analyze the samples and perform material response (MR) simulations of the experiments. A series of tools were used to analyze the samples after the experiments, including X-ray computed tomography (XRCT) scans to analyze the recession profile of the samples (Fig. 1.b), X-ray photoelectron spectroscopy (XPS) scans to study the composition of the surface coating on the samples (Fig. 1.c), and scanning electron microscopy (SEM) micrographs to observe the differential ablation between the fiber and matrix regions of the C/C composite ((Fig. 1.d) [1]. Three experimental conditions for the graphite samples were modeled with a multidimensional material response solver, the material response module of the Kentucky aerodynamic and thermal-response system (KATS-MR) [2]. The results of the MR simulations are compared to the back-face temperature of the samples recorded during the experiments, and the recession profiles collected from the XRCT scans. The comparison indicates that the MR solver obtains good agreement with the lower power experiments, but worsens as the laser power increases, as shown in Figs. 1.f and 1.g.

Keywords: Laser ablation, sublimation, XRCT, SEM, material response.

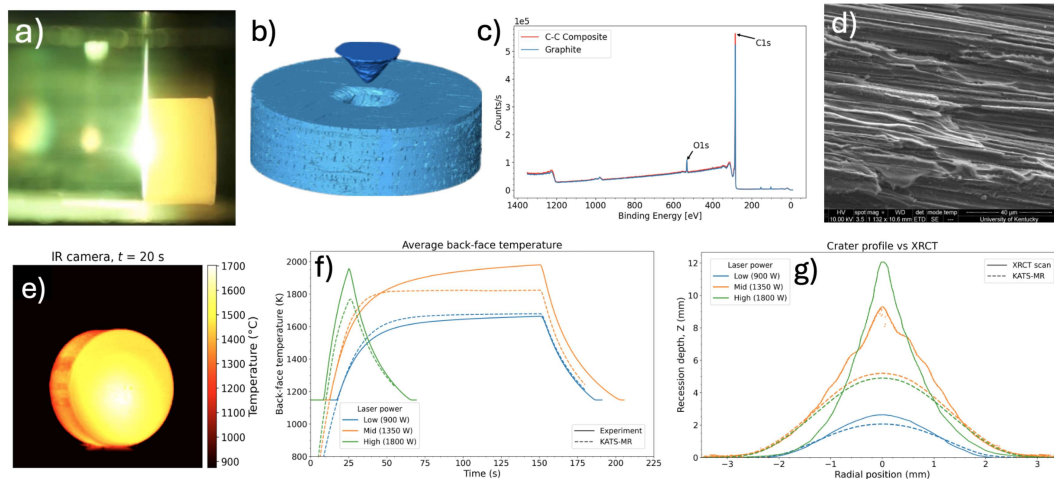


Figure 1: Graphical abstract. a) Graphite sample during experiment. b) XRCT scan of graphite sample. c) XPS scan results of C/C composite and graphite samples. d) SEM micrograph of C/C sample showing thinning of fibers. e) Frame of FLIR camera data recorded during experiment. f) Comparison of average back-face temperature between MR simulations and experiments. g) Comparison of recession profile between MR simulations and experiments.

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Influence of Carbon Fibers on the Pyrolysis of Carbon-Phenolic Ablative Heat Shield Materials

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Abstract

After extensive investigation of the temperature gradient-dependent pyrolysis of three carbon-phenolic materials (cured SC-1008, PICA-D, and 3MDCP-IL), it was observed that the presence or absence of carbon fibers altered the pyrolysis mechanisms and molar yields of the volatile gases. To understand the effects of the fibers, gaseous pyrolysis products of carbon fiber samples used in the carbon-phenolic composites were obtained as a function of sample temperature (room temp – 1200 °C) at selected temperature gradients (~ 1 and ~ 6 °C s⁻¹) using a molecular beam mass spectrometry technique. These yields were then studied to infer the decomposition mechanisms, and they were compared to the yields from the pyrolysis of the phenolic materials to identify differences and possible interactions. From the temperature-dependent yields from FiberForm (Figure 1a), the precursor to PICA-D, it is clear that there are oxide species present on the carbon fibers, which may react to release H₂O, CO₂, and CO (example mechanisms shown in Figure 1b). The presence of oxide species in FiberForm helps to explain why the temperature-dependent yields during the pyrolysis of cured SC-1008 resin contain a greater ratio of volatile aromatics vs. H₂O and CO compared to the yields of the two carbon-phenolic composites, PICA-D and 3MDCP-IL. This is because FiberForm can introduce additional condensation reactions between the oxidized species and resin, leading to increased crosslinking and the preservation of carbon through the formation of more thermally stable bonds. Additional effects of carbon fibers on the pyrolysis mechanisms of carbon-phenolic composites were also observed, such as a catalytic reaction caused by metal impurities and the production of N₂ at high temperatures if the fibers were derived from polyacrylonitrile.

Keywords: Carbon fiber, oxidation, ablative heat shields, pyrolysis, gaseous products, crosslinking.

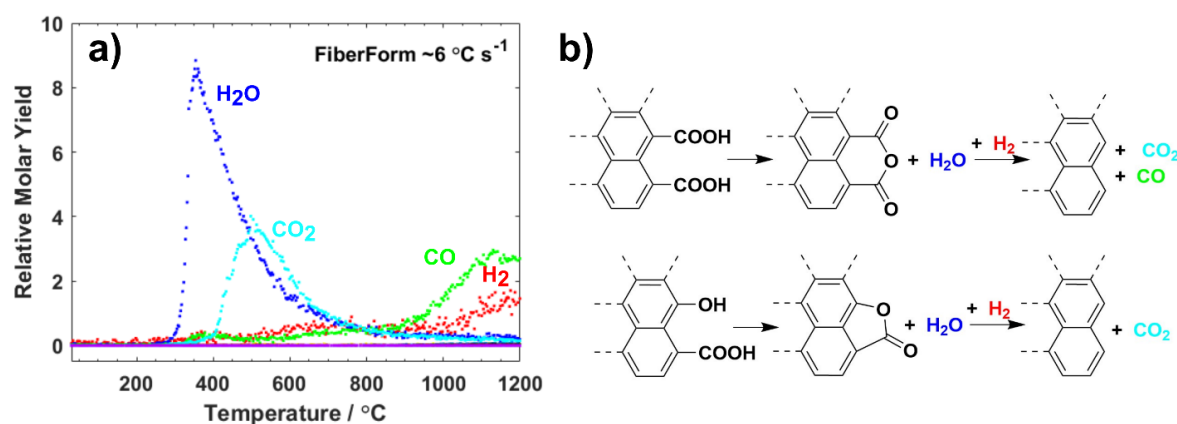


Figure 1. (a) Example of relative molar yields of the pyrolysis products that evolve from FiberForm with a temperature gradient of ~ 6 °C s⁻¹. (b) Reaction of neighboring oxide species present on carbon fibers.

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Development of Thermal Protection Systems Research Capabilities at NMSU

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Abstract

The design of ablative Thermal Protection Systems (TPS) requires a thorough understanding of material behavior across multiple length scales. These materials exhibit complex multiscale responses, making it essential to connect microstructural characteristics with macroscopic thermophysical, transport, and chemical properties.

In this work, we present an update on the development of a new laboratory at New Mexico State University dedicated to the characterization and study of TPS materials for hypersonic applications. The laboratory integrates a suite of experimental techniques, including microscopy and micro-computed tomography for microstructural characterization, Transient Plane Source measurements for thermal conductivity, pycnometry, and TGA/DSC for thermal and compositional analysis. These capabilities are complemented by computational approaches for interpreting and upscaling material properties, including Lattice Boltzmann Method simulations of permeability and ongoing work on plasma-flow modeling.

Two custom experimental facilities are also under development. The first is designed to investigate plasma-material interactions, following the approach of Anderson [1], while the second uses laser heating to study carbon deposition and related gas-surface interactions [2, 3]. Initial testing of the laser-heating facility demonstrates the capability to reach temperatures relevant to high-temperature TPS material response.

Future efforts will focus on integrating these capabilities and expanding the laboratory toward species quantification and the characterization of fracture and mechanical properties, with the broader goal of improving the understanding and design of ablative TPS materials.

Keywords: ablation, thermal protection systems

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A coupled framework for mesoscale ablation

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Abstract

Ablation of thermal protection systems (TPS) during hypersonic entry is governed by microstructural features of carbon/carbon composites. This work presents a coupled numerical framework for mesoscale ablation that integrates an enthalpy-based Lattice Boltzmann Method (LBM) heat transfer solver with the Interfacing Surface Triangles and voxels for Heterogeneous MULTiphysics Simulations (ISTHMUS) library [1, 2]. ISTHMUS bridges voxelized material domains, which capture complex TPS microstructures at high fidelity, with surface mesh-based flow solvers using the marching windows method. Aerothermal heat fluxes and surface ablation rates computed by the direct simulation Monte Carlo (DSMC) method on the evolving surface mesh are mapped to boundary voxels through the ISTHMUS flux mapping module, after which the LBM solver advances the thermal state within the material. Consumed voxels are then removed, and the ISTHMUS motion mapping module regenerates the surface mesh for the next DSMC iteration. The framework enables time-accurate simulation of thermally resolved, microstructure-evolving ablation.

Keywords: mesoscale ablation, Lattice Boltzmann Method, ISTHMUS, TPS, marching windows

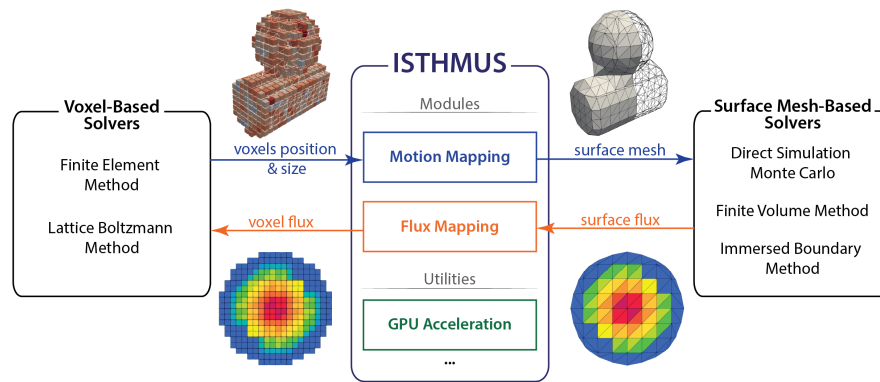


Figure 1: Overview of the ISTHMUS coupling framework and its role as a bridge between the surface mesh-based flow solver (DSMC) and the voxel-based material domain (ELBM).

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August 10, 2026

Self-Consistent Modeling of an RF Plasma Flow Reactor

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Abstract

Radio-frequency (RF) plasma flow reactors provide controlled environments for studying plasma surface interactions relevant to high-temperature material response and ablative thermal protection systems. Such reactors have also been used to investigate plasma assisted oxidation and nitridation of graphite for high-temperature gas surface interaction studies [1]. Previous characterization of the argon reactor studied by Abuyazid *et al.* relied on a bulk plasma density inferred from electrical measurements, which was subsequently used as an upstream condition for modeling charged-species decay in the spatial afterglow [2]. The RF discharge responsible for generating and sustaining this bulk plasma, however, was not spatially and temporally modeled.

The objective of this work is to determine how RF power deposition, electric fields, electron energy, plasma chemistry, and charged-particle transport establish and sustain the experimentally observed bulk plasma.

A two-dimensional axisymmetric wedge representation of the ring electrode quartz-tube geometry is modeled using SOMAFOAM [3] to directly simulate plasma generation. The model couples charged species drift diffusion transport, electron energy, plasma chemistry, and the electrostatic field. A $J \cdot E$ RF power controller regulates the excitation amplitude according to the computed volumetric power deposition. Simulations focus initially on the 13.56 MHz, 10 Torr argon discharge operated experimentally at 20 W forward RF power.

A representative transient solution captures the spatial development of the discharge and the formation of metastable Ar* within the RF-driven plasma region, as illustrated in Fig. 1. The transient discharge exhibits sensitivity to the initial charged-species seed density.

The resulting model links the imposed RF operating conditions to self-consistent predictions of plasma properties and species transport, and will ultimately be used to predict the reactive environment delivered to graphite surfaces in plasma-assisted oxidation, nitridation, and ablation experiments.

Keywords: Thermal Protection Systems, RF Plasma, Plasma Surface Interaction, Plasma Modeling

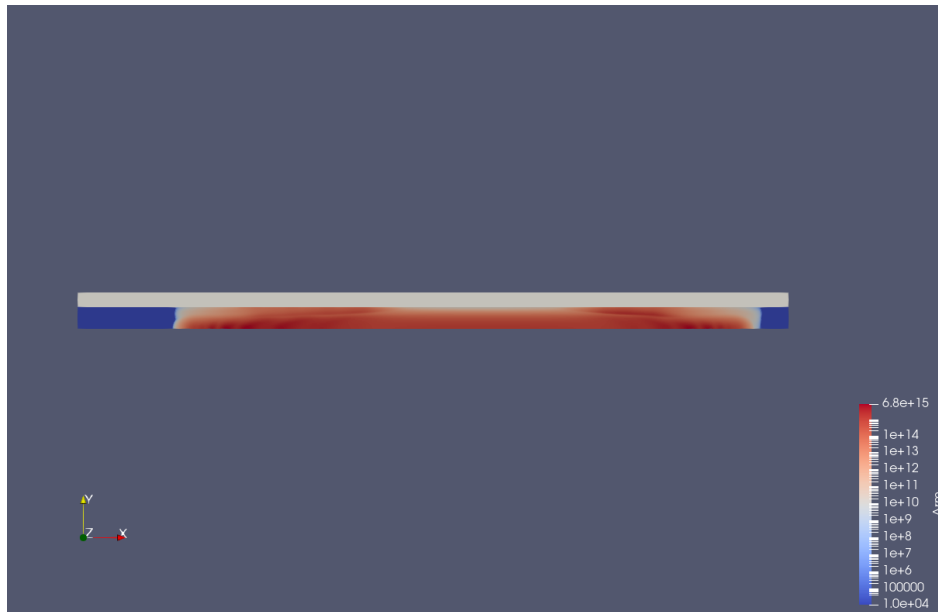


Figure 1: Spatial distribution of the metastable argon number density

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Oxygen-Carbon Reactions in FiberForm Investigated with Molecular Beam Mass Spectrometry

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Abstract

Accurate prediction of oxidation in porous thermal protection system (TPS) materials requires reliable modeling of finite-rate ablation chemistry and gas transport. A free molecular flow (FMF) reactor experiment, depicted in Figure 1a, has been designed to provide measurements of oxygen reactivity in porous carbon materials such as FiberForm, the carbon-fiber precursor used in phenolic impregnated carbon ablator (PICA). The setup utilizes a thermal cracking oxygen beam source to expose a thin piece of heated FiberForm to controlled gas streams containing O_2 or a mixture of O and O_2 , both of which can react with the carbon structure. Reactive products are collimated by two apertures and directed into a quadrupole mass spectrometer with an electron impact ionizer. Relative fluxes of O , O_2 , CO , and CO_2 were calculated utilizing different flow rates, sample temperatures, and cracking ratios. The results reveal that the presence of O atoms increases carbon reactivity through enhanced CO production when compared to the same O_2 flow rate without O atoms, seen in Figure 1b, with nearly negligible CO_2 production. The trend of increased reactivity while increasing FiberForm temperature and O -atom concentration was observed at three flow rates. The observed increase in CO flux is less than predicted if every O atom reacts to form CO , suggesting that oxygen recombination may compete with other oxidation pathways. This experiment provides useful data for carbon ablation modeling and may contribute to uncertainty reduction in porous TPS performance with the objective of enabling reliable, high-fidelity simulation capabilities for future atmospheric entry missions.

Keywords: Carbon oxidation, FiberForm, gas-surface interactions, free molecular flow reactor.

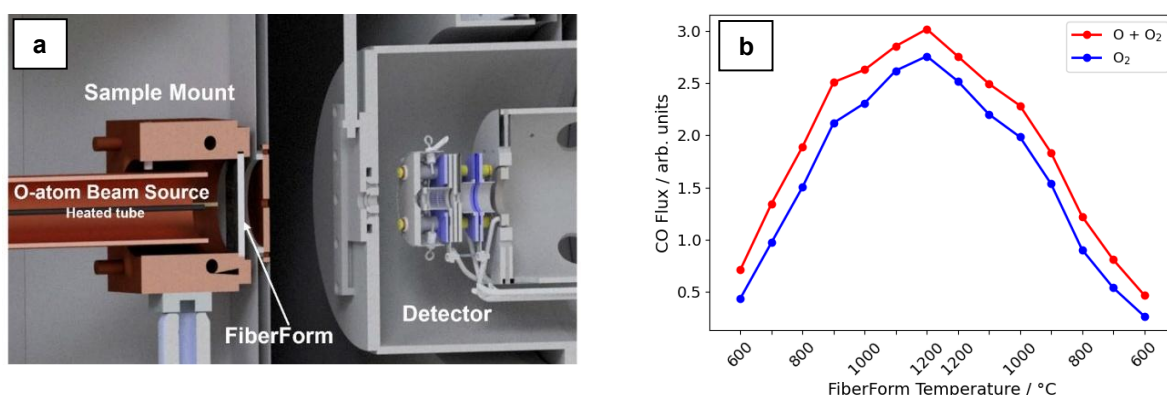


Figure 1. (a) Schematic diagram of the free molecular flow reactor setup, illustrating the thermal cracking oxygen beam source (OBS) coupled with the molecular beam sampling mass spectrometer. (b) Plot of CO product flux as a function of FiberForm temperature with a reactive stream of pure O_2 (blue curve) and with a reactive stream containing 12% O and 88% O_2 (red curve). Both conditions used the same flow rate; thus, the results indicate an increased net reactivity in the presence of O atoms.

This work was supported by NASA (Grant No. 80NSSC21K1117).

Kalman Filtering and RTS Smoothing for Arc-Jet Sample Edge Tracking

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Abstract

Accurate and temporally consistent measurements of test-article recession are required to characterize material response during arc-jet ablation experiments. However, image-based boundary measurements are often affected by segmentation noise, brightness variations, and frame-to-frame variability.

This work extends arcjetCV [1] with filtering methods for tracking the evolving boundaries of hemispherical and ISO-Q test articles.

Two boundary-tracking approaches based on Kalman filtering [2] were implemented. The first applies a point-wise Kalman filter followed by a Rauch–Tung–Striebel smoother [3] to individual boundary-point locations. The second applies the same filtering and smoothing framework to a reduced set of geometry-dependent shape parameters.

The point-wise method reduces local frame-to-frame fluctuations while preserving spatial details along the detected boundary. The shape-parameter method provides a compact and geometrically constrained estimate of the sample contour. Figure 1 illustrates the two approaches for a hemispherical test article. Both methods improve temporal consistency and support more robust estimation of surface recession from arc-jet imagery.

The two filtering approaches provide complementary representations of boundary evolution and improve the reliability of image-based recession measurements during arc-jet experiments.

Keywords: ablation, thermal protection systems, arc-jet testing, Kalman filter, Rauch–Tung–Striebel smoother, boundary tracking, recession measurement

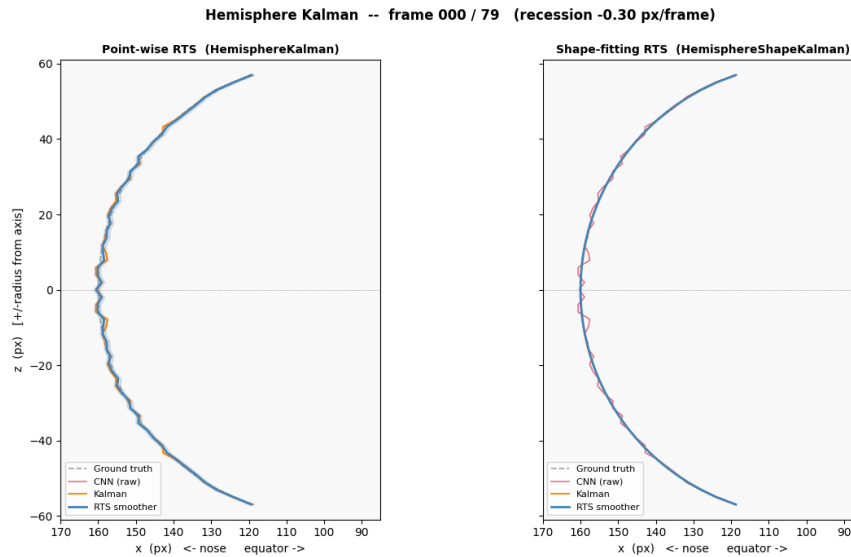


Figure 1: Comparison of point-wise and shape-parameter Kalman filtering with RTS smoothing for hemispherical boundary tracking.

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BEAST: Expanding Sustainable Data Infrastructure for High-Enthalpy Facilities

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Abstract

Reproducible, data-driven thermal protection system (TPS) research requires that experimental records from high-enthalpy testing be consistently structured, traceable, and accessible across campaigns and institutions. In practice, however, arcjet and plasma facilities data remain largely fragmented: raw diagnostics are stored in ad hoc formats, material sample histories are disconnected from test conditions, and metadata standards are absent, precluding systematic cross-campaign analysis and long-term reuse. *BEAST* (Backend for Experiment Analysis, Storage, and Traceability) is an open-source, web-based platform that addresses these limitations by providing a unified, queryable infrastructure for high-enthalpy ground-test data [1]. First presented at the 15th Ablation Workshop [2], *BEAST* has since undergone significant development. The platform ingests and structures multi-channel time-series diagnostics, facility configurations, and material property records within a common provenance model, ensuring end-to-end traceability from raw sensor acquisition to reduced experimental quantities. A versioned material library links specimen identity and processing history to the specific runs in which each sample was tested. An integrated modeling workbench enables training and evaluation of regression models directly on archived experimental data, supporting condition interpolation and the construction of empirical material response databases. Beyond its original deployment at NASA Ames Research Center, *BEAST* has been designed to be facility-agnostic, with ongoing efforts to extend its adoption to other facilities. Its modular architecture accommodates heterogeneous diagnostic setups and facility types, and its future open-source distribution allows institutions to build on a common data standard rather than maintaining isolated, bespoke solutions. *BEAST* is further integrated within a broader ecosystem of companion tools: *arcjetCV* [3] extracts recession rates and shock standoff distances from high-speed video using computer vision, and *miniSTARscan* [4] provides sub-minute, portable photogrammetric surface reconstruction of test articles before and after exposure. All tools share a common data schema, enabling seamless ingestion of surface geometry, imagery, and time-series data into a single, coherent experimental record.

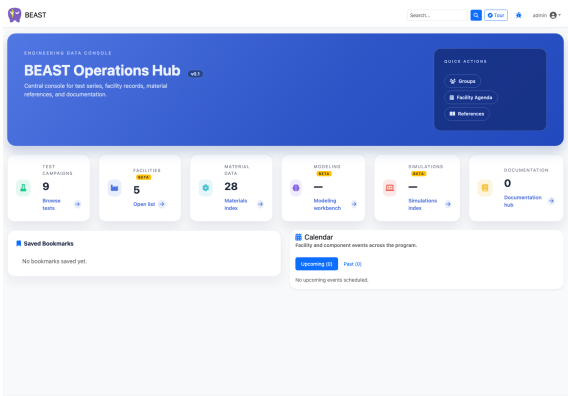
Keywords: High-enthalpy testing, data management, thermal protection systems, ablation, material traceability, experimental database

References

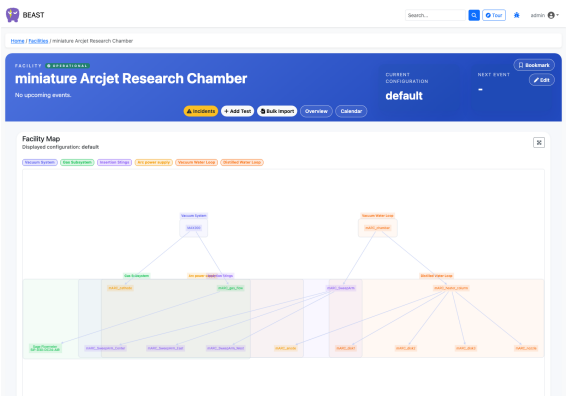
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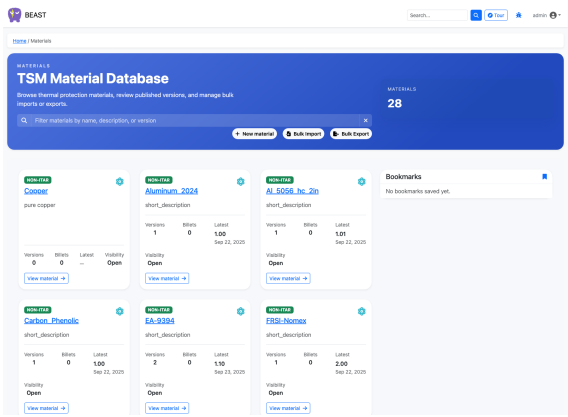
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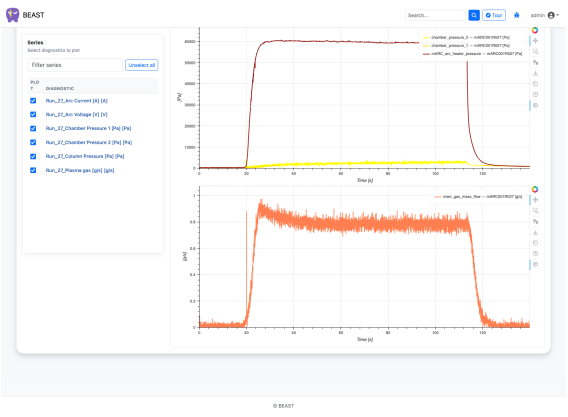
(a) BEAST home dashboard.



(b) Facility configuration page with interactive topology map.



(c) Versioned material property library interface.



(d) Single-run diagnostic time-series view.

Figure 1: Overview of the BEAST web interface.

Development of a Modular Coupling Framework for Aerothermodynamic and Material Response Simulations

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Abstract

The prediction of material response in hypersonic flows requires accurate coupling between the external aerothermodynamic flowfield and the material thermal response. While computational fluid dynamics and material response solvers have individually reached a high level of maturity, coupling these solvers efficiently remains an active area of research. In the present work, a coupling framework is developed using the preCICE coupling library [1] to couple the SU2 [2] computational fluid dynamics solver with heat conduction and material response solvers, including SU2 and the Porous Material Analysis Toolbox (PATO) [3]. The framework allows the exchange of interface quantities, including surface temperature and heat flux, while retaining the existing numerical capabilities of the individual solvers. The coupling methodology is initially evaluated using SU2 for both the fluid and solid domains through a conjugate heat transfer problem. The coupled results for a wind-tunnel test of hypersonic flow over a circular tube [4] are compared with the corresponding experimental measurements of surface pressure, temperature, and heat flux. Figure 1 shows the temperature contours for both the fluid and solid domains, along with a comparison between the simulated and experimental data at the interface after 4 seconds of physical time. The results show good agreement with the experimental data. The developed framework provides a basis for coupling nonequilibrium hypersonic aerothermodynamics with material response and for investigating different numerical approaches and coupling strategies.

Keywords: hypersonic flows, aerothermodynamics, material response, multiphysics coupling, preCICE

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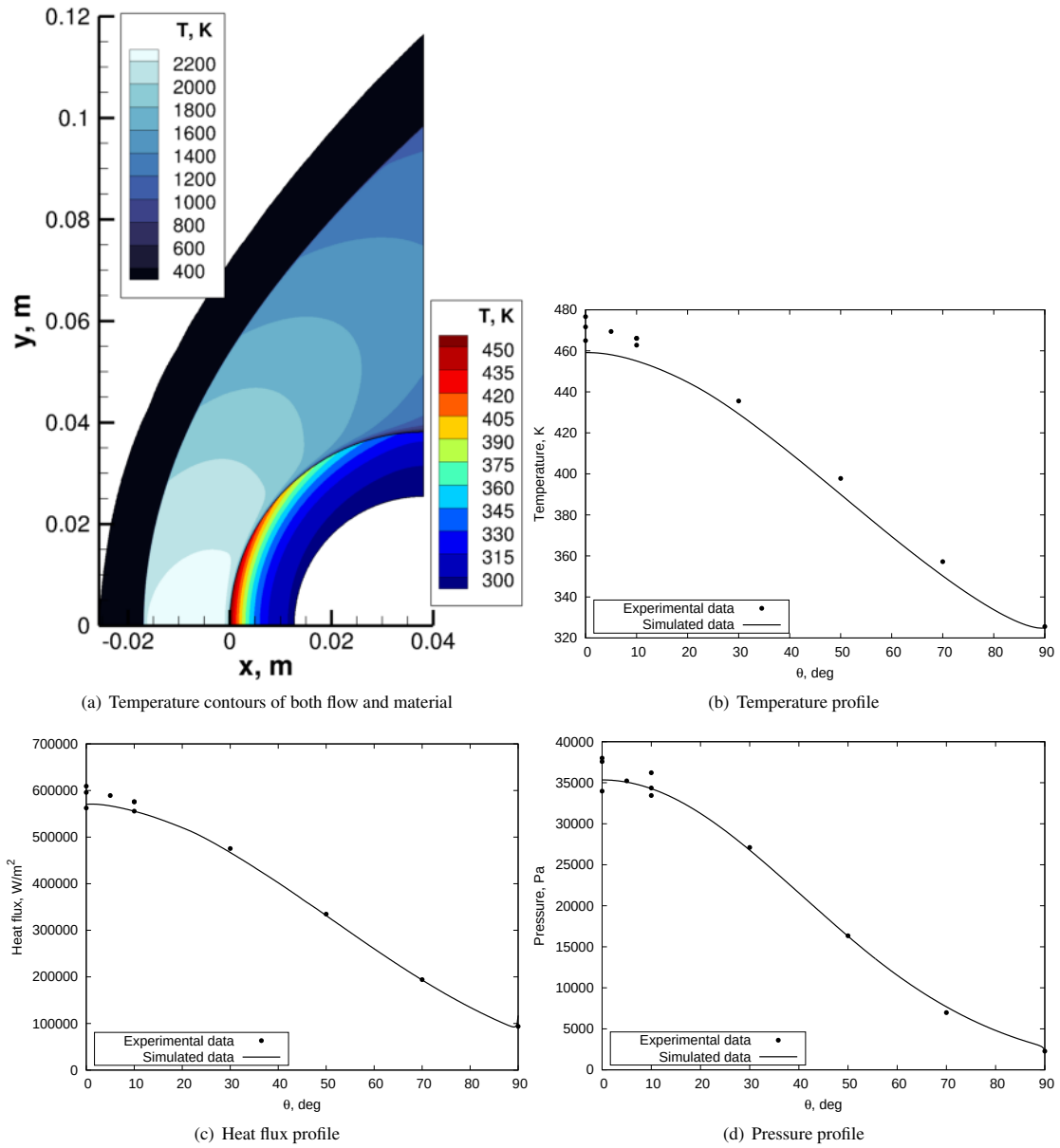


Figure 1: Comparison of interface quantities from the SU2-SU2 simulation with the Wieting experiments [4] after 4 seconds of physical time.

Inclusion of backward rates to the air-carbon ablation model

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Abstract

The air-carbon ablation (ACA) model is a recently developed finite-rate oxidation and nitridation model anchored with data from molecular beam experiments [1]. Although the ACA model contains rates for the dominant processes, it does not include backward rates and does not satisfy detailed balance. Therefore, a system that integrates the ACA model would not reach thermochemical equilibrium. A process is presented to ensure that finite-rate ablation models, such as the ACA model, are consistent with thermodynamic equilibrium. The backward rates are derived for the ACA model to allow CO, CO₂, and CN to interact with the surface. Additional reactions are incorporated into the model to ensure it reaches a thermochemical equilibrium state that minimizes the Gibbs energy of the air-carbon system. Thermodynamic consistency is verified through 0-D reactor calculations (Fig. 1), and CFD results are presented that compare the as-published ACA model with the modified ACA model that includes backward rates [2].

Keywords: Air-carbon ablation, oxidation, backward rates, equilibrium, thermodynamics

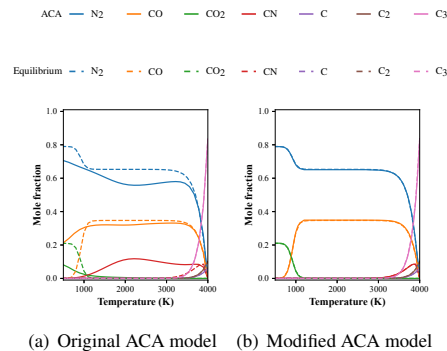


Figure 1: Equilibrium composition of the original and modified ACA model compared to thermodynamic equilibrium at a pressure of 1 atm.

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High-throughput molecular dynamic simulation for char-yield prediction and materials screening

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Abstract

Polymer pyrolysis and subsequent char formation strongly influence material performance in applications including spacecraft thermal protection systems. However, char yield (Y_C) remains difficult to predict directly from molecular structure because experimental datasets are limited and large-scale synthesis and testing are costly. This work develops a benchmark-validated molecular dynamics (MD) framework for quantitative Y_C prediction and material screening. The simulation protocol was systematically benchmarked against experimental char-yield data for 51 C/H/N/O polymers across 240 simulation configurations, varying pyrolysis temperature (2000, 2250 and 2500 K), initial density (0.30 and 0.50 g/cm³), polymer chain weight (800 and 1600 g/mol), simulation duration (0.5, 1, 1.5 and 2 ns) and the molecular-size criterion used to distinguish volatile species from char. The optimal modeling parameters provided an excellent prediction accuracy for experimental Y_C of 51 C/H/N/P polymers, with $R^2=0.916$, MAE=4.4 wt.% and RMSE=7.4 wt.% (Figure 1a). Representative simulation results from the benchmarking set show both complete volatilization of polystyrene with predicted and experimental Y_C of 0 wt.% (1c) and substantial char formation in poly(ether ether ketone) with a predicted Y_C of 46.9 wt.% compared with 46.5 wt.% experimentally (Figure 1b). Following validation, the optimized workflow has been applied to more than 1,000 polymers with ongoing simulations targeting approximately 10,000 polymers for large-scale structure-property analysis and materials screening.

Keywords: Polymer pyrolysis, ReaxFF, Data augmentation, Benchmarking, Thermal protection system

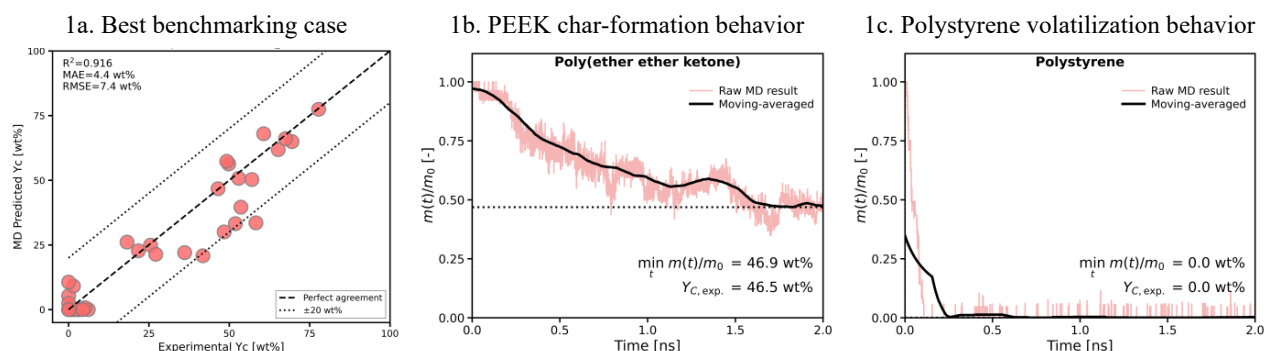


Figure 1: Reactive MD benchmarking across 51 CHNO polymers: (a) Parity plot of predicted vs. experimental char yield ($R^2 = 0.916$), (b) PEEK char formation, (c) Polystyrene volatilization.

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In Situ Synchrotron Microtomography of Intumescence and Pyrolysis in Microballoon-Filled RTV Thermal Protection System Gap Fillers

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Abstract

Room-temperature-vulcanizing (RTV) silicone is widely used as a high-temperature adhesive and gap-filling material in tiled ablative thermal protection systems, including architectures based on Phenolic Impregnated Carbon Ablator (PICA) and Avcoat [1–3]. During entry-relevant heating, RTV undergoes pyrolysis accompanied by substantial changes in porosity and volume, including intumescence, which can alter local gap geometry and the thermal response of the heat shield. In this work, synchrotron X-ray micro-computed tomography (micro-CT) is used to investigate the three-dimensional evolution of microballoon-filled RTV during controlled heating and pyrolysis. Time-resolved tomographic measurements acquired at the Advanced Light Source at Lawrence Berkeley National Laboratory capture the internal microstructure from the virgin state through initial swelling, pre-pyrolysis expansion, active pyrolysis, and the resulting decomposed structure. The evolution of individual microballoons and larger void structures is evaluated to quantify their contribution to bulk expansion, pore growth, coalescence, and material degradation. The experimental matrix includes constrained and unconstrained specimens, inert and oxidizing environments, and as-received and dried material conditions. Preliminary analysis shows pronounced microstructural evolution coincident with bulk swelling and pyrolysis, motivating direct tracking of void growth and coalescence across temperature-correlated scans. These measurements provide a microstructural basis for connecting RTV formulation and boundary conditions to intumescence and pyrolysis, and provide experimental data for development and validation of physics-based material-response models for ablative thermal protection systems.

Keywords: room-temperature-vulcanizing silicone, thermal protection systems, microballoons, pyrolysis, intumescence, synchrotron microtomography, micro-CT

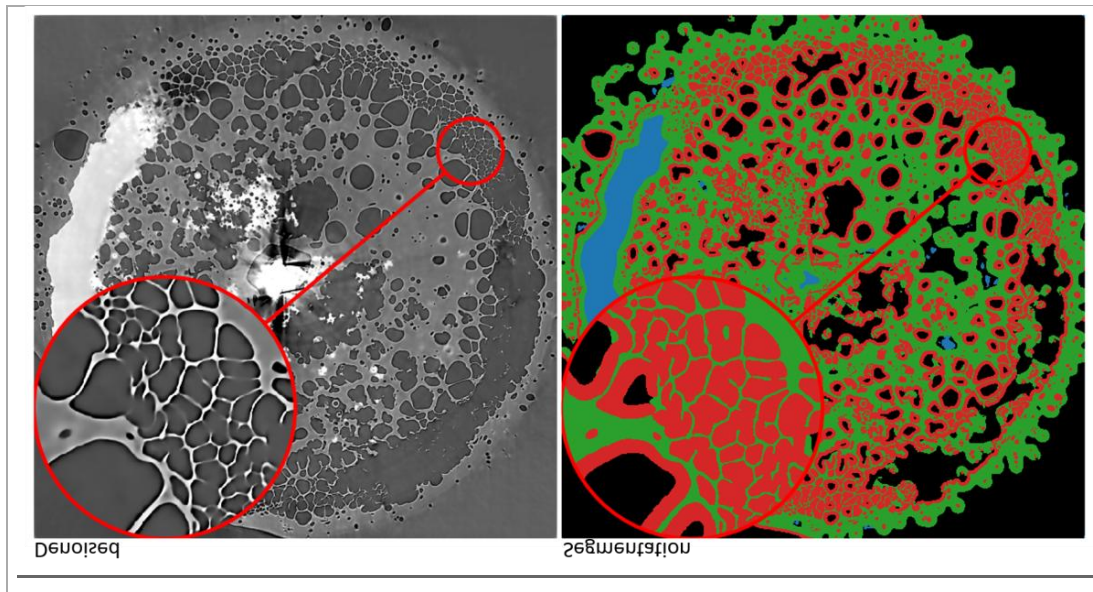




Figure 1: Denoised and Segmented micro-CT visualization of microstructural evolution in microballoon-filled RTV during heating.

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Discussing Ablation Test-Case #4

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Abstract

A new Ablation Workshop test case was proposed last year to tackle the challenge of modeling the mechanical response of TPS materials [1]. Following the philosophy of the previous test cases, the objective was to define a simple and fully specified benchmark that can be used for code-to-code comparison. As agreed, this Test-Case #4 proposition builds directly on Test-Case #1 [2] and extends it to solid mechanics by accounting for thermal expansion and pyrolysis-induced shrinkage [3]. While Test-Case #1 was formulated as a one-dimensional problem, the introduction of solid mechanics motivates an extension to three dimensions, where deformation and stress development can be more meaningfully assessed. Transversely isotropic mechanical properties are defined for TACOT and applied to a 20 cm $\times$ 20 cm $\times$ 5 cm square tile, subjected to the thermal conditions of Test-Case #1, with a prescribed temperature of 1644 K applied to the heated surface for 60 s. Simplified 1D and 2D configurations may also be considered to investigate the influence of dimensionality on the predicted deformation and stresses. Time will be left for discussions with the objective of finalizing material properties, geometry, boundary conditions, and quantities of interest.

Keywords: ablation, thermal protection systems, pyromechanics

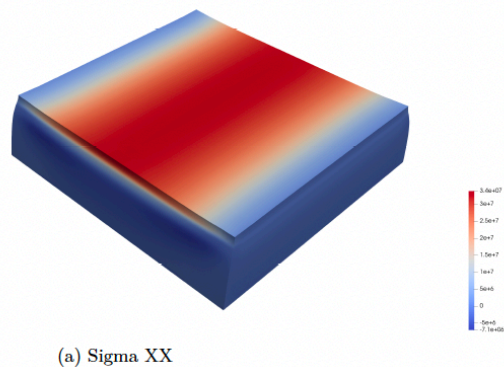


Figure 1: Displacements and in-plane stress at 1 minute: preliminary PATO results.

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Reactive Coverage Model Fit to Graphite Oxidation Dataset Across Pressure Regimes

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Abstract

Recent years have witnessed a focused effort on the development of high-fidelity carbon ablation models, with the Air-Carbon Ablation (ACA) model [1] representing the state-of-the-art. These models include many different reaction mechanisms for carbon removal via oxidation, nitridation and sublimation and provide chemical kinetic boundary conditions for ablation calculations in both material response and computational fluid dynamics solvers. Meanwhile, engineering applications and first-order thermal protection system designs often rely on closed form solutions of carbon oxidation. These are attractive because they do not require solving the full law-of-mass-action surface-kinetics system at runtime. Examples such as the ubiquitous Park 1976 model [2] and the surface coverage formulation by Nagle and Strickland-Constable [3] (1962) provide reasonable predictions with minimal overhead, supporting mid-fidelity engineering analyses. Following the legacy work of Nagle and Strickland-Constable, we propose a simplified oxidation model grounded on classical adsorption theory, that provides an algebraic expression for steady-state surface coverage. Model parameters are fit against a comprehensive review of literature data on high temperature graphite oxidation. Our findings suggest that integrating a simple surface adsorption process can substantially improve upon the orders of magnitude variations predicted by first-order reaction-coefficient models such as Park 1976. The proposed model captures the change in carbon mass flux with pressure and the peak in reactivity as a function of surface temperature. It also shows remarkable agreement with the empirical datasets across ten orders of magnitude in pressure, between 10^{-5} – 10^5 Pa, and temperatures between 1000 and 2400 K. The proposed model suggests that the effective reaction order may depart from first order. This new model form builds upon legacy theory and takes the advantage of modern data, to provide a predictive tool for carbon oxidation across test facilities, from molecular beams to arcjets. Yet it maintains the agility of engineering level models to provide fast calculations across flight regimes.

Keywords: empirical model, adsorption theory, gas-surface interactions, graphite, oxidation

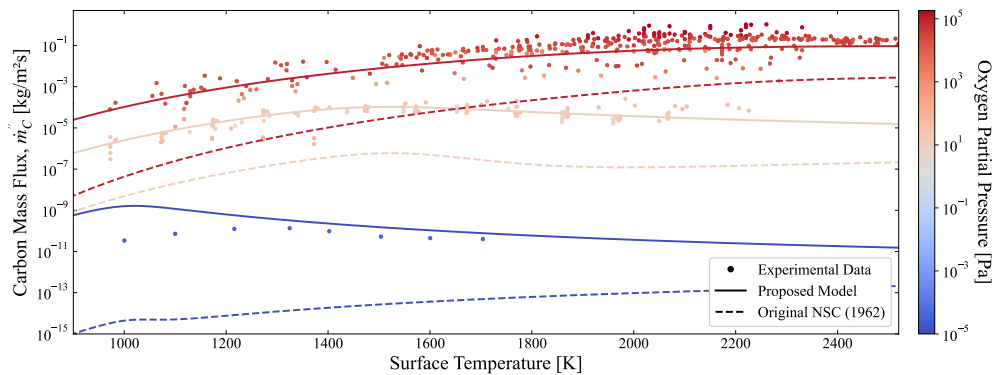


Figure 1: Carbon mass flux of isotropic graphite reacted with molecular oxygen across a range of temperatures and pressures. The proposed model is fit to the experimental data set and compared to the original model of Nagle and Strickland-Constable (NSC).

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KRUPS: Overview of the KREPE-3 flights and beyond.

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Abstract

The Kentucky Reentry Universal Payload System (KRUPS) is a low-cost experimental platform designed to collect flight data during atmospheric reentry. Its third orbital mission, the Kentucky Re-Entry Probe Experiment (KREPE)-3, expands from five capsules flown on KREPE-2 to twelve, incorporating multiple thermal protection systems (TPS), spectral seeding materials, four new capsule geometries, and upgraded avionics with higher transmission rates. The presentation will describe the KREPE-3 mission architecture, capsule and TPS designs, preflight verification, and flight operations. A common internal housing and redesigned avionics stack enabled efficient integration across the different capsule configurations. The presentation will also discuss the future of the KRUPS platform, including the upcoming KRAKEN mission and KREPE-4, which will further expand its capabilities for low-cost hypersonic and atmospheric-entry flight experimentation.

Keywords: flight campaign; atmospheric entry; thermal protection systems



Figure 1: KRUPS capsules of the KREPE-3 flight.

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Physics-Constrained Trajectory-Coupled Scientific Machine Learning for Accelerated End-to-End Hypersonic Entry Design

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Abstract

WildKATS (Wall-Informed Learning Dynamics of the Kentucky Aerothermodynamics and Thermal-response System) is a physics-constrained machine-learning framework for affordable, trajectory-scale prediction of coupled hypersonic aerothermodynamics and thermal protection system (TPS) response. WildKATS directly predicts both the global flow field and surface quantities, including heat flux, pressure, and shear stress. The framework is trained using multifidelity CFD spanning trajectory conditions, gas composition, and wall states. Preliminary 2D axisymmetric results demonstrate a complete 157-s entry trajectory in under 11 minutes using only 60 high-fidelity training cases, providing approximately five orders of magnitude wall-clock acceleration with errors below 2%. WildKATS is coupled to 3-DoF trajectory and material-response solvers to evolve the flow and ablating TPS simultaneously, including pyrolysis, surface chemistry, mass loss, and recession.

Keywords: Machine Learning; Ablation; Hypersonics; Thermal Protection Systems

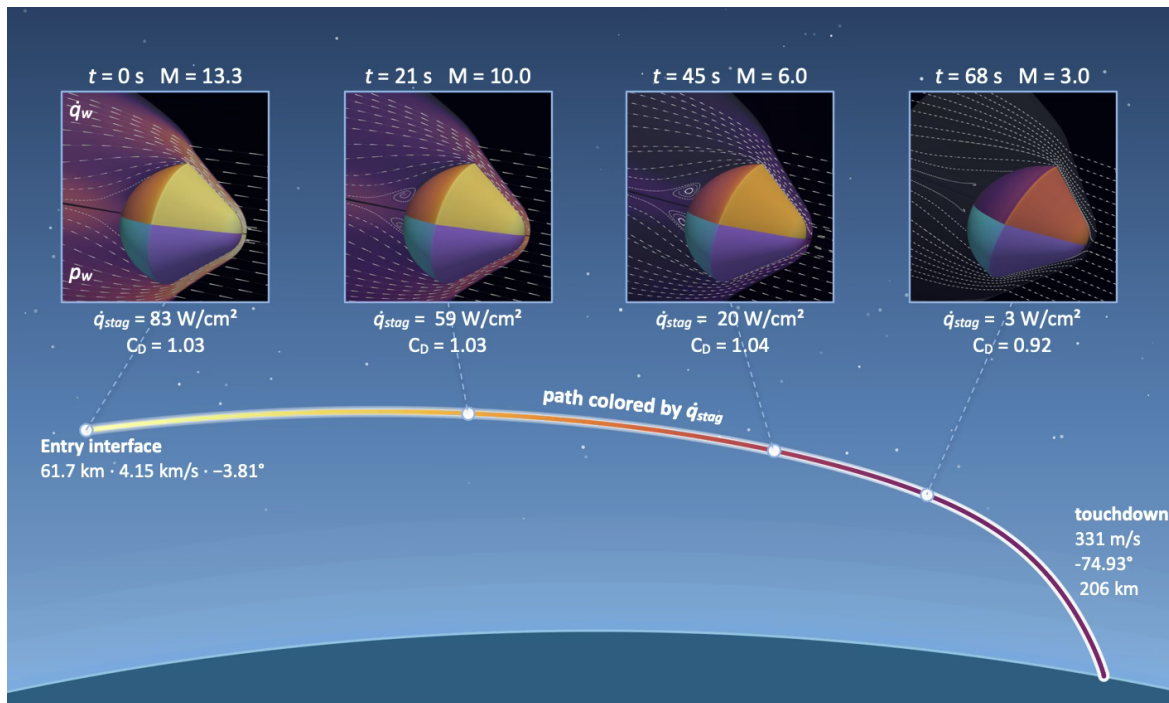


Figure 1: Trajectory of the KRUPS capsules during the KREPE-2 flight: all 1631 solutions (every 0.1 s step) returns a full field; $\dot{q}$ and C_D drive the dynamics.

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Artificial Neural Network for Material and Dimensional Characterisation of Thermally Induced Distortion in Extruded Metals

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Abstract

Metal Material Extrusion (MMEX) additive manufacturing enables the cost-effective fabrication of complex metallic components [1], yet its wider adoption is constrained by nonlinear shrinkage and geometric distortion occurring during thermal debinding and solid-state sintering [2]. Accurate dimensional and morphological characterisation of these thermally induced deviations is essential for establishing reliable quality metrics and process control [3]. In this work, an Artificial Neural Network (ANN) framework is developed to characterise and map complex, non-uniform displacement fields directly from initial Computer-Aided Design (CAD) models to final thermally processed geometries. Benchmark truncated pyramid geometries were additively manufactured, debinded, and sintered to consolidate the metal particles. The post-processed parts were then digitized using high-precision 3D optical surface scanning to extract spatial coordinate meshes and quantify the exact point-to-point geometric deviations from the initial CAD design. The ANN model successfully learned the underlying nonlinear thermal shrinkage mechanics, yielding over a 98% improvement in 3D displacement prediction relative to conventional uniform scaling. By demonstrating high-fidelity characterisation of macroscopic thermal distortion, this data-driven methodology establishes a foundational baseline that can be extended to inverse CAD compensation, high-tolerance aerospace and high-temperature structural applications.

Keywords: Metal Material Extrusion, Machine Learning, Geometric Distortion, Sintering Shrinkage, CAD Compensation, Dimensional Accuracy

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Tomography And Lattice Boltzmann Exploration

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Abstract

Computed Tomography (CT) and segmentation of material microstructures provide valuable insights that can be directly linked to their physical properties and performance [1, 2]. Deep learning-based segmentation offers an efficient approach for reconstructing complex three-dimensional material architectures, while pore-scale simulations can use these digital microstructures to predict effective transport properties [3].

In this work, we develop an integrated framework combining 3D CT segmentation with Lattice Boltzmann Method (LBM) simulations to characterize transport through complex Thermal Protection System (TPS) materials. The framework is demonstrated using syntactic foam, a heterogeneous material composed of a foam resin matrix, glass fibers, microballoons, and open air voids.

A custom 3D U-Net architecture implemented in PyTorch is used to perform multiclass volumetric segmentation of CT data, distinguishing the main structural constituents of the material. The resulting segmented microstructures are then used as computational domains for a three-dimensional LBM solver based on the D3Q19 lattice model. The solver, implemented in Python using JAX for GPU-accelerated computation, applies the Guo forcing method to drive flow through the pore space and calculates permeability from the resulting velocity field using Darcy's law [4].

The segmentation framework successfully reconstructs the three-dimensional distribution of the different material constituents and produces digital microstructures suitable for pore-scale simulations. The LBM solver was validated using idealized sphere-packed geometries, reproducing dimensionless permeability values consistent with published reference data [5]. Additional validation is being performed using randomized fiber microstructures generated with PuMA before application to CT-derived material geometries.

The combined segmentation and LBM framework provides a pathway from experimental CT imaging to physics-based prediction of effective transport properties in complex TPS materials. Ongoing work focuses on applying the validated solver directly to segmented CT volumes and evaluating permeability as a function of material microstructure, with the broader goal of supporting microstructure-property relationships and computational qualification of TPS materials.

Keywords: porous microstructure, 3D U-Net, Lattice Boltzmann Method

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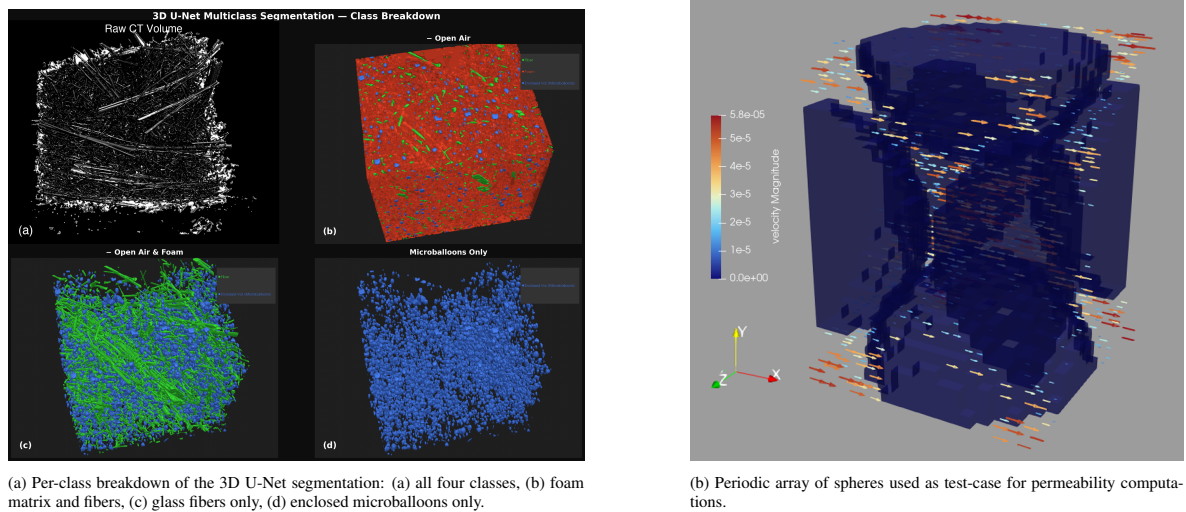


Figure 1: Segmentation and permeability simulation examples.

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Insights into Meteor Physical Properties from Faint Meteor Flares

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Abstract

This work investigates the rapid brightening phenomena, known as meteor flares, that occur during the fragmentation and ablation of small grains from faint meteors. Recent studies have shown that over 90% of faint meteors exhibit some sign of fragmentation [1]. Current challenges include quantifying the impact of fragmentation on key meteor properties, such as bulk densities, and determining whether tensile strengths derived from the smaller meteor population are consistent with previous fireball studies.

By targeting flares from the mm–cm meteor population that ablate at high altitudes, we remove the need for complex hydrodynamical models and break degeneracies between erosion and grain sizes in modern meteor fragmentation models [2]. We constrain the meteor physical properties by simultaneously modeling the observed light curve and deceleration profile, using high-resolution imagery from the mirror-tracking system of the Canadian Automated Meteor Observatory [3] and advances in Bayesian inversion with dynamic nested sampling [4, 5].

Early results indicate that including wake modeling of grains behind the meteor can provide additional constraints on grain parameters such as the upper and lower grain mass distributions for certain meteor morphologies. This work highlights the complexity of fragmentation in meteor ablation modeling and the importance of high-resolution wake observations for improving models of meteor physical structure.

Keywords: fragmentation, meteor physics, ablation modeling

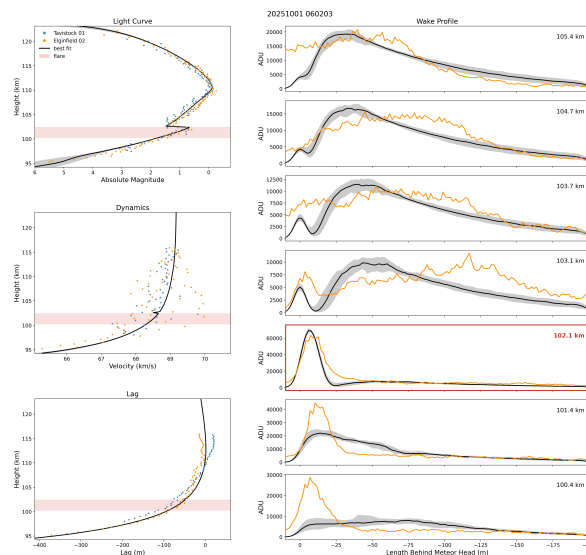


Figure 1: Observed light curve, dynamics, and wake profile from the two sites (Tavistock, blue; Elginfield, orange) of the Canadian Automated Meteor Observatory. The dynamic nested sampling fit (black) is derived only from the light curve and deceleration profile. The rapid brightening due to ablated grains is highlighted in red for each panel. The wake profile traces the particle size distribution, as smaller grains with larger surface area to mass ratios lag behind the meteor head. Wake observations before and after the flare highlight changing particle distributions in orange that are not captured by current fragmentation models in gray.

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Experimental study of internal thermo-chemical response of ablators by means of a laser-heated facility

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Abstract

Thermal protection systems (TPS) are integral to protecting spacecraft upon atmospheric entry as external temperatures reach above 2000 °C. During re-entry, the resin that fills the porous space of the TPS is burned, forming pyrolysis gases that flow through the porous char. These gases then react with the hot carbon-rich char in processes such as coking or oxidation, thus directly degrading the performance of the TPS by changing thermal conductivity, internal pressure, and permeability.

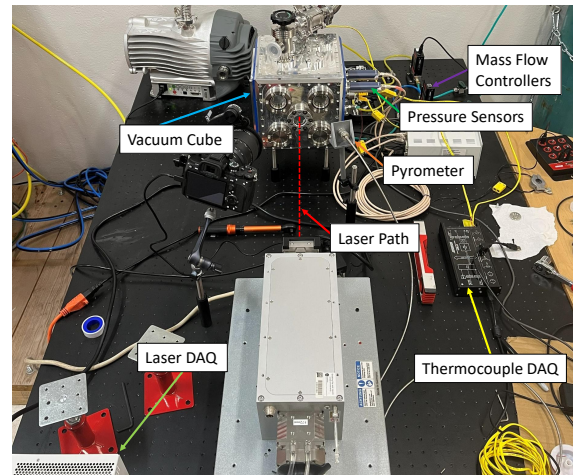
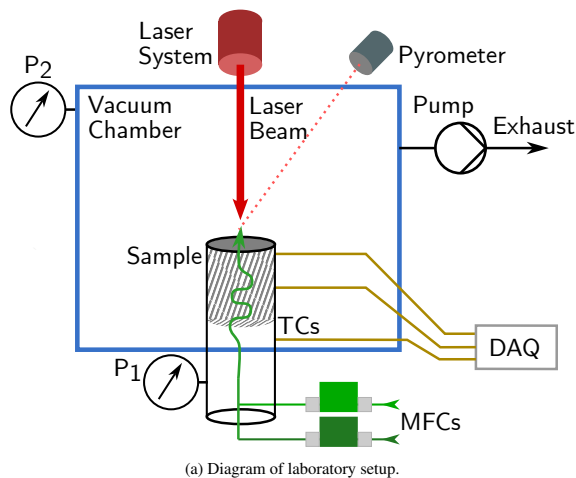
This work uses an experimental approach involving a high-power (1.5 kW) continuous-wave laser to heat carbon-fiber preform samples in a vacuum chamber, while representative pyrolysis gases are flowed through the porous sample to simulate resin decomposition and carbon deposition.

By replicating the internal behavior of ablators during atmospheric re-entry conditions, the system provides a controlled environment for investigating various phenomena, including thermal response, sample behavior under extreme conditions, and, of particular interest, the gas-surface interactions (GSI) between the sample and the pyrolysis gases. Preliminary testing is being conducted with argon and nitrogen for system verification.

Post-test analyses include SEM imaging and micro-CT to show the effects of coking, pore evolution, and spatial distribution in the porous felt. These results will be used to develop and validate predictive chemical models for future, improved thermal protection systems.

Keywords: carbon, laser heating, gas-surface interactions, coking

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SCAM: (not so) Simple Code for Ablative Materials

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Abstract

We present SCAM, an open, lightweight Python solver for modeling the ablation and thermal response of porous thermal protection system materials. SCAM originated as an experiment to assess the performance of modern large language models in implementing well-established conservation equations and numerical methods for ablation response [1]. It has since evolved into an agile framework for testing material response models, post-processing high-enthalpy wind tunnel experiments, and performing rapid trade studies. SCAM was developed with Claude Code using the Sonnet 5 model for tasks such as code generation, refactoring, documentation, and test development. Model correctness was established through human review, unit testing, and verification cases. The code uses an implicit finite-volume formulation with a Newton-coupled surface energy balance and either discrete or continuous (ALE) surface recession. Pyrolysis-gas transport includes Darcy flow through the porous char and optional elemental mass-fraction transport for equilibrium chemistry. Surface ablation is closed by either tabulated B' balances or a live equilibrium-chemistry backend (Cantera or Mutation++), including blowing corrections and advective enthalpy terms. The material library includes several TPS classes, including ablative organic, carbon, hybrid, and silicone-based materials. The implementation is verified against analytical solutions where available and compared against benchmark ablation test cases [2, 3]. SCAM calculations match PATO [4] predictions of surface temperature to within ~ 5 K ($<0.5\%$) and recession to within $<3\%$ across chemistry-backend and layered-material variants. The software is released open-source under the MIT License.

Keywords: ablation, thermal protection systems

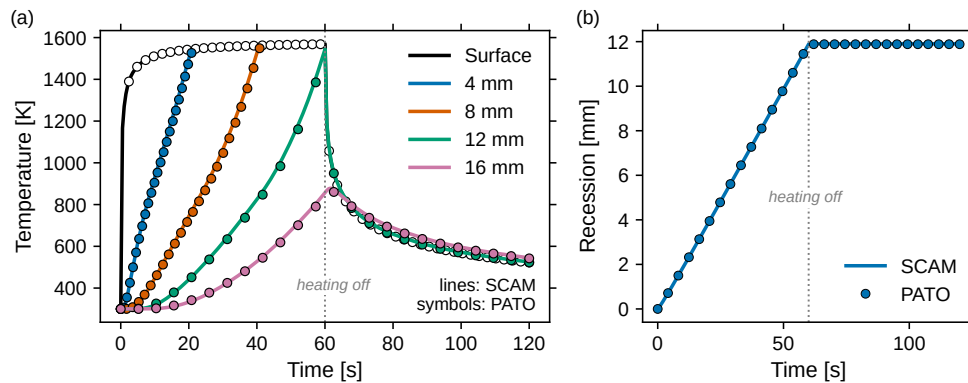


Figure 1: SCAM is verified against PATO across the full Ablation TestCase Series #1 and #2. Here, good agreement is shown for Ablation TestCase 2.2.

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Development of a Mach 2.3 Supersonic Indraft Wind Tunnel and Experimental Investigation of Swirling Jets in Crossflow

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Abstract

A small-scale supersonic indraft wind tunnel (SIWT) was designed, constructed, and tested at New Mexico State University (NMSU) to provide a flexible experimental facility for investigating supersonic jet–crossflow interactions relevant to scramjet propulsion. The facility employs a modular two-dimensional converging–diverging nozzle and a 7,500-gallon vacuum tank, enabling operation from Mach 1.5 to 4, with the present study conducted at Mach 2.3. The nozzle was designed using the method of characteristics with boundary-layer correction, and the rectangular test section provides optical access for advanced flow diagnostics. The newly constructed facility was used to investigate the interaction of an underexpanded swirling jet with a Mach 2.3 supersonic crossflow. A variable-swirl injector with an 11-mm exit diameter was mounted flush with the top wall of the test section, and the jet was injected normal to the crossflow. Preliminary free-jet experiments using focused schlieren were first conducted to identify suitable operating conditions and swirl levels. These experiments showed that moderate swirl produced a stable bow shock and near-field recirculation structure, while stronger swirl generated a more unsteady flow. Jet-in-crossflow experiments were subsequently performed using laser-sheet Mie-scattering visualization at an estimated jet pressure ratio of 12.7. The results show that introducing swirl significantly modifies shear-layer development and downstream mixing while flow recirculation in the near field is not confirmed. The study demonstrates the capability of the newly developed NMSU SIWT for investigating complex supersonic jet–crossflow phenomena and establishes a foundation for future quantitative velocity-field measurements.

Keywords: crossflow, supersonic, indraft tunnel

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Stability Analysis of Hypersonic Thermochemical Nonequilibrium Boundary Layer

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1 Introduction

The larger lift-to-drag ratio of winged space planes (such as the Space Shuttle) considerably decreases aerothermal loading (allowing for reusable heat shields), reduces g-loads on passengers, and substantially increases cross range capability. As such vehicles enter the thicker atmosphere, laminar-turbulent transition can substantially increase the heat loads, potentially leading to heat shield damage or, in the worst case, entire loss of the vehicle Figure ?? . This makes accurate predictions of laminar-turbulent transition indispensable for heat shield design and trajectory analysis. The flight trajectory of winged space planes crosses several distinct aero-thermo-dynamic regimes that are characterized by vibrational excitation, dissociation of oxygen and nitrogen, and ionization. The effect of these mechanisms on laminar-turbulent transition is not well understood [1]. We are employing both Linear Stability Theory (LST) and Direct Numerical Simulations (DNS) to investigate the thermo-chemical non-equilibrium effects on laminar-turbulent transition. Both codes have been validated for reference cases from the literature [2, 3, 4].

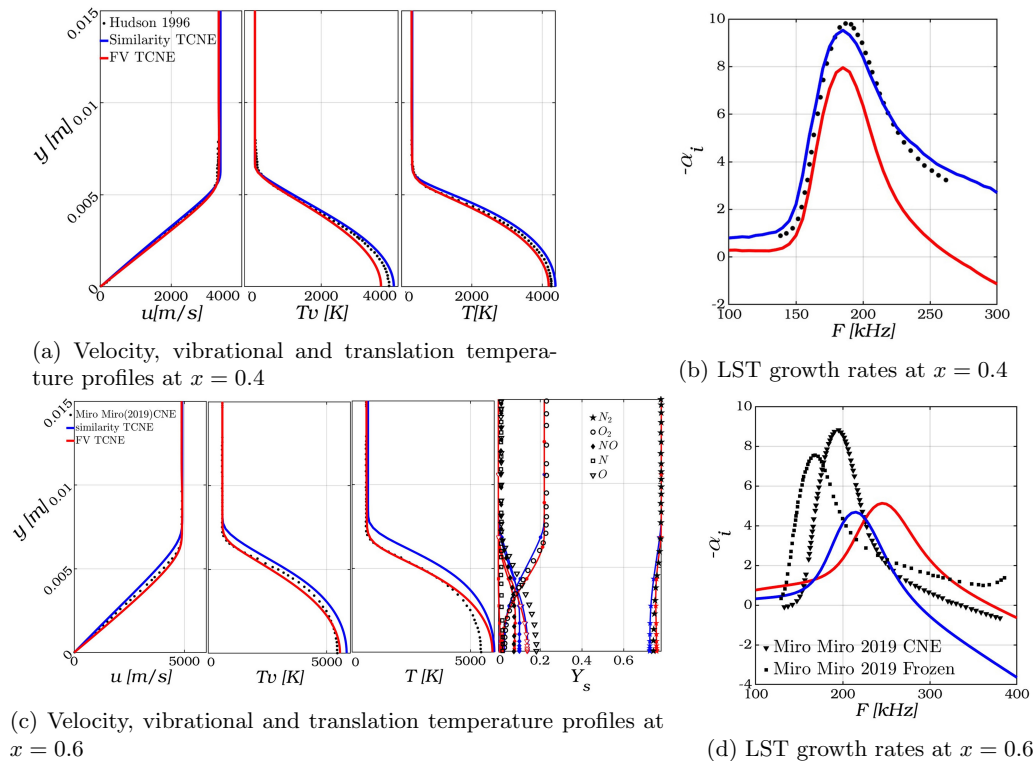


Figure 1: Baseflows profiles from finite-volume code and stability results

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