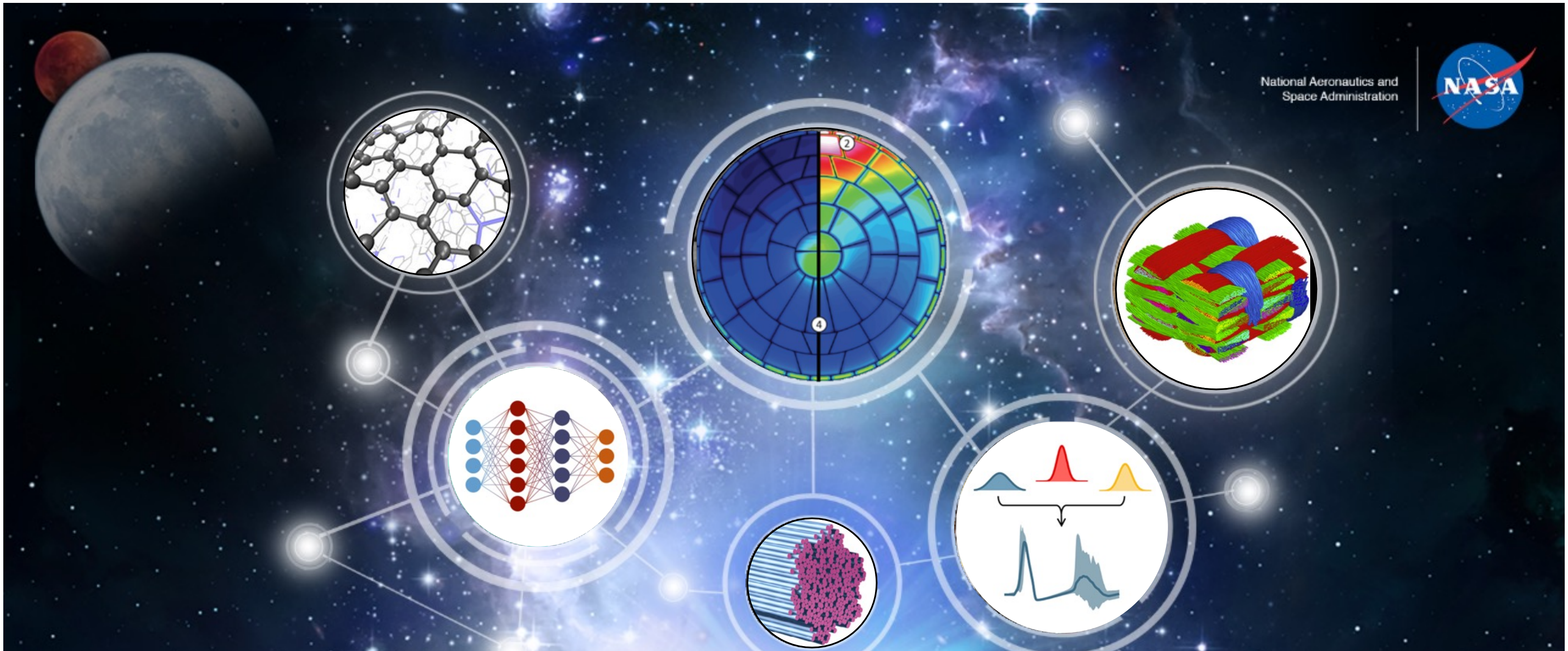


Overview of Ablation Modeling at NASA

Justin Haskins,[1] Michael Barnhardt,[1] Eric Stern,[1] Jeremie Meurisse,[1] Arnaud Borner,[1] Federico Semeraro,[1] Adam Amar,[2] Joshua Monk,[1] Brody Bessire,[1] Jay Feldman[1]

[1]NASA Ames Research Center

[2]NASA Johnson Space Center

Ablation Workshop 2022 | November 9th, 2022

Contribution Acknowledgement

Teams and Modeling Efforts

Entry Systems Modeling (ESM) Leadership
ESM/Icarus Team
ESM/Predictive Material Modeling Team
ESM/Certification by Analysis Team
JSC Ablation Modeling Team
ARC Ablation Subject Matter Experts
ARC Experimentalists

NASA ARC/JSC Contributors

Michael Barnhardt
Aaron Brandis, Eric Stern
Joseph Schulz
Georgios Bellas-Chatzigeorgis
Jeremie Meurisse
Arnaud Borner
Federico Semeraro
Sergio Izquierdo Fraile
Joseph Ferguson
Jon Thornton
Krishnan Swaminathan Gopalan
Nagi Mansour
Lauren Abbott
BJ Tucker
Andrew Santos
Simon Schmitt
Adam Amar
Justin Cooper
Brandon Oliver
Frank Milos
YK Chen
Joshua Monk
Brody Bessire
Jay Feldman

Outline

- Stakeholders
- Ablation Tools and Applications
- University Support
- Takeaways

Ablation Modeling Stakeholders

Ablation modeling at NASA has a broad range of stakeholders – government organizations, research & flight projects, and universities/institutes

Government Organizations

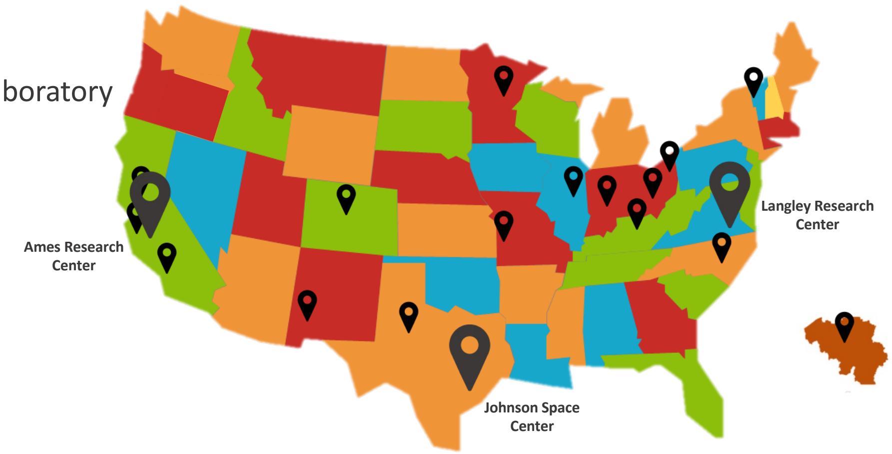
NASA Ames Research Center
NASA Langley Research Center
NASA Johnson Space Center
NASA Glenn Research Center
Sandia National Laboratories
Lawrence Livermore National Laboratory
Air Force Research Laboratory

Missions/Flight Projects

Dragonfly/DrEAM
Commercial Crew/Orion
Mars2020/MEDLI2
Mars Sample Return
DAVINCI
KREPE

NASA Research Projects

Entry System Modeling Project (ESM)

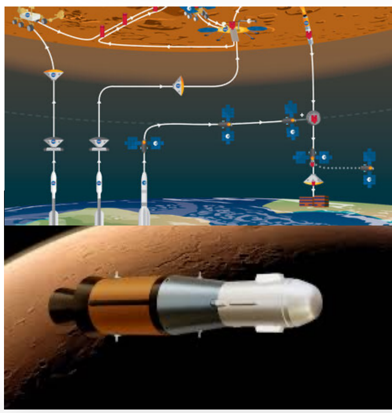


Universities/Institutes

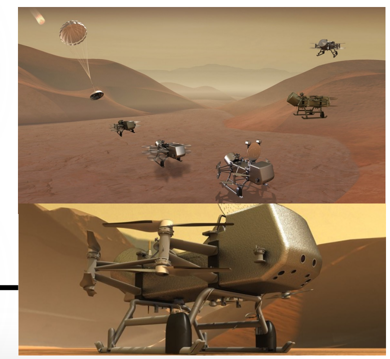
University of Colorado Boulder
University of Kentucky
University of Illinois Urbana Champaign
Stanford University
University of Minnesota
University of California Los Angeles
Purdue University
Von Karman Institute for Fluid Dynamics
Missouri University of Sci. & Tech.
University of Virginia
University of North Carolina

A Few Mission Timelines

Mars2020/MEDLI2



Mars Sample Return (MSR)



Dragonfly/DrEAM

2010 2020 2030 2040

Entry/Ablation Challenges Challenges

Mars2020/MEDLI2

Challenge
Flight data from instrumentation showed influence of silicone overcoat on ablation – required development of models accounting for new chemistry

Mars Sample Return (MSR)

Challenge
Strict reliability requirements and use of new woven TPS for the Earth Entry System (EES) – requires quantifying property variability and understanding MMOD risks

Dragonfly/DrEAM

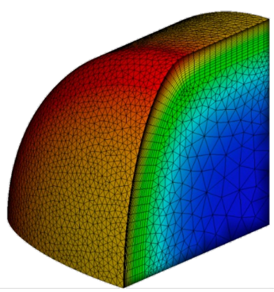
Challenge
Unique high radiation environment at Titan heats main seal beyond qualified limits – requires multi-D modeling of complicated geometries.

2010 2020 2030 2040

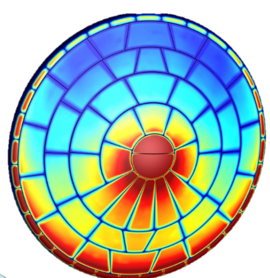
Research & Development Strategy

Recent investments in TPS ablation tool development focused on meeting challenges of flight projects – mediated by the Entry Systems Modeling (ESM) and flight projects

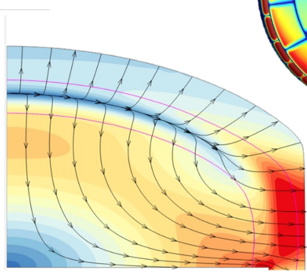
Modernizing Material Response Codes



Icarus

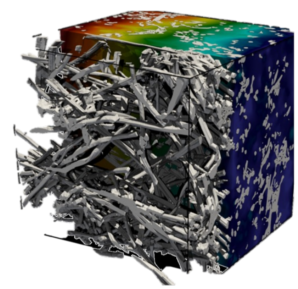


PATO

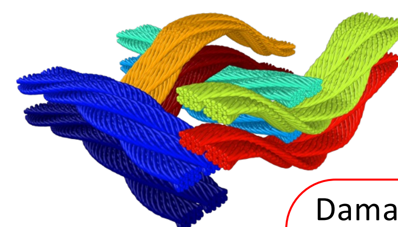


CHAR

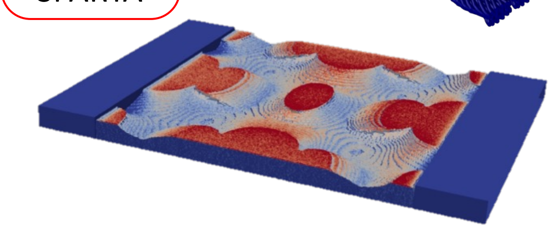
Maturing Microscale Capabilities



PuMA



Damage Models

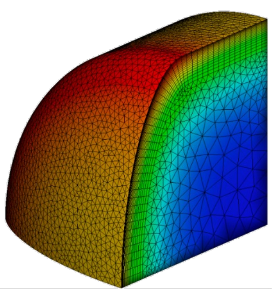


SPARTA

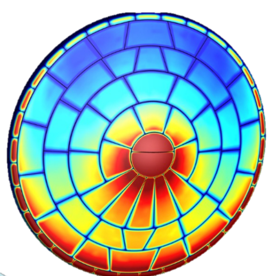
Research & Development Strategy

Recent investments in TPS ablation tool development focused on meeting challenges of flight projects – mediated by the Entry Systems Modeling (ESM) and flight projects

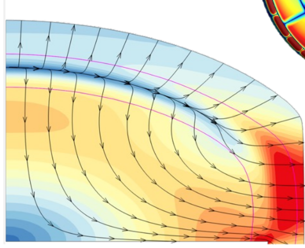
Modernizing Material Response Codes



Icarus

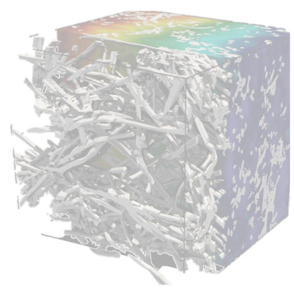


PATO



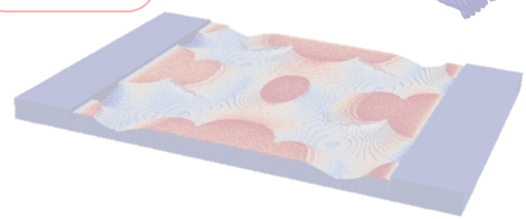
CHAR

Maturing Microscale Capabilities



PuMA

Damage Models



SPARTA

Material Response Code Timeline

CMA
- **C**harring **M**aterials **A**blation
- Moyer & Rindal (1968)
- Aerotherm
- Finite Difference
- Node-dropping ablation

FIAT
- **F**ully **I**mplicit **A**blation and **T**hermal response program
- Chen & Milos (1999)
- Implicit time stepping
- Finite Volume
- Grid Compression
- MSL, Stardust, Mars2020, many others

Titan & 3dFIAT
- 2D & 3D FIAT
- Chen & Milos (2001,2005)
- Coupled with GASP/DPLR

PATO
- Lachaud & Mansour (2014)
- multi-D, finite volume, OpenFOAM
- Simple to implement new models
- Collaborate with partners

CHAR
- Amar et al. (2016)
- multi-D, finite element
- Used for Orion/Commercial Crew

Icarus
- Schulz et al. (2017)
- multi-D, finite volume, parallel
- US3D integration
- mission design tool

1968 — 1999 — 2000's — 2010's

Icarus Material Response Solver

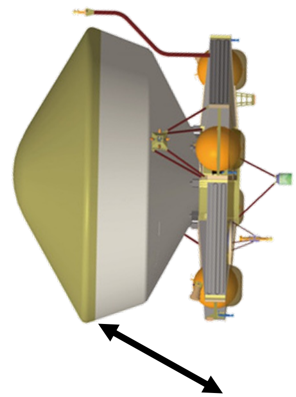
Principal NASA user base is focused on design for science missions and other flight projects

- Design for Dragonfly and MSR-EES
- Limited distribution on an as-need basis for primarily government/contractor use

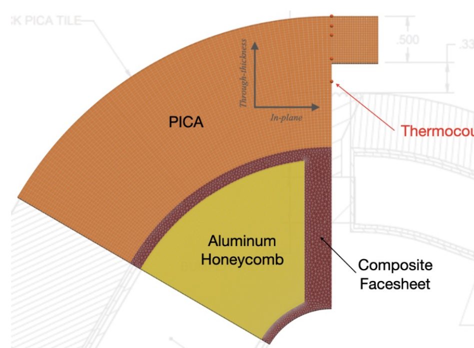
Three-dimensional, unstructured, finite volume material response solver

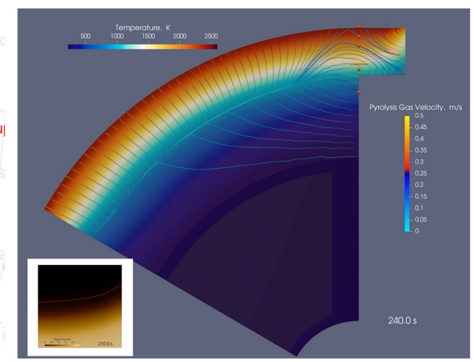
- NASA developed through ESM with efficient suite of solvers and parallelism developed
- Models ablating, pyrolyzing, vaporizing, or melting materials with wide-ranging boundary conditions
- Other enabling features include coupling to US3D, Mutation++, and DAKOTA/SALib

Current research activities include examination of MMOD effects on ablation, integration of dust erosion effects, and refinement of coupling to US3D packages



PICA "tooth" design being traded for Dragonfly heatshield to provide protection of main seal – performance assessment requires multi-D capability





POCs: Stern and Schultz

Icarus Material Response Solver

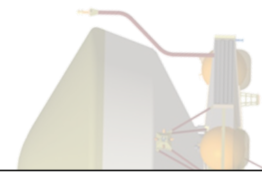
Principal NASA user base is focused on design for science missions and other flight projects

- Design for Dragonfly and MSR-EEV
- Limited distribution on an as-need basis for primaril

Three-dimen material resp

- NASA de of solve
- Models materia
- Other e Mutation++, and DAKOTA/SALib

Current research activities include examination of MMOD effects on ablation, integration of dust erosion effects, and refinement of coupling to US3D packages



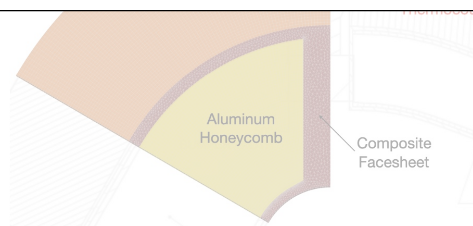
PICA "tooth" design being traded for Dragonfly heatshield to
nain seal –
sment
pability

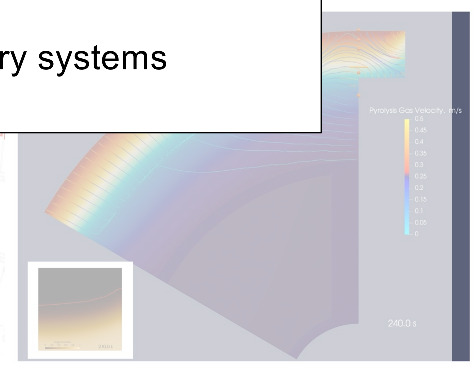
Talks on Icarus:

Eric Stern – Overview and recent developments of Icarus

Joseph Schulz – Material response simulations of the Dragonfly capsule using Icarus

Olivia Schroeder – Ares: A multi-physics modeling framework for entry systems





PATO – Porous material Analysis Toolbox based on OpenFOAM

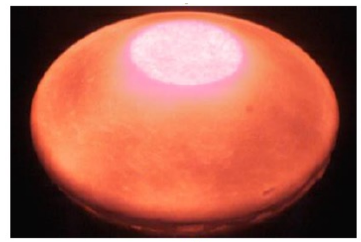
Principal NASA user base is focused on developing new models for TPS material analysis

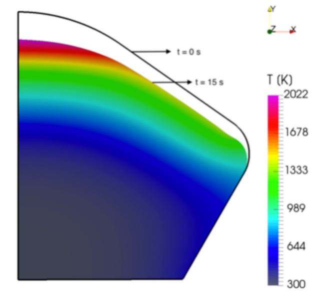
- Evaluated the influence of NuSil coating on ablation
- Open distribution and a collaborative platform for interacting with industry/academia

One-, two-, and three-dimensional, unstructured, finite volume material response solver

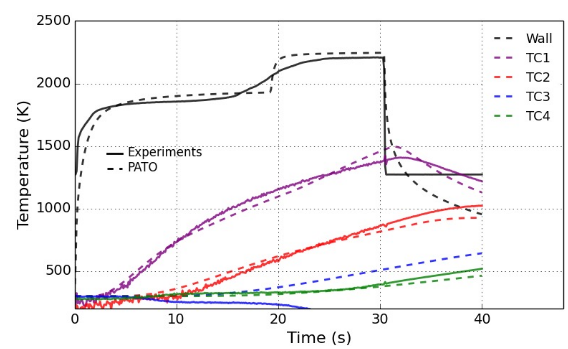
- NASA developed through ESM and built on OpenFOAM
- Rich array of boundary conditions with finite-rate capability and advanced material models (fracture)
- Other enabling features include coupling to DPLR, Mutation++, and DAKOTA

Current development efforts include new physical models accounting for shear erosion, RTV fencing, and coating surface chemistry as well as improved coupling to CFD for reconstruction analysis





PATO characterization of NuSil coating on PICA in arc jet test conditions – geared to develop better models for recession of MSL and Mars2020



POCs: Meurisse, Bessire, and Panerai

PATO – Porous material Analysis Toolbox based on OpenFOAM

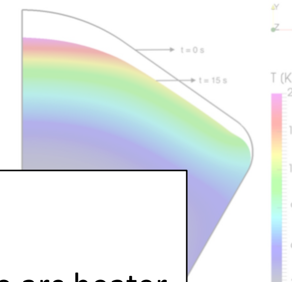
Principal NASA user base is focused on developing new models for TPS material analysis

- Evaluated the influence of Nusil coating on ablation
- Open distribution and a collaborative platform for interacti

One-, two-, a
finite volume

- NASA de
  OpenFO
- Rich arra
  capabilit
- Other er
  Mutation++, and DAKOTA

Current development efforts include new physical models accounting for shear erosion, RTV fencing, and coating surface chemistry as well as improved coupling to CFD packages



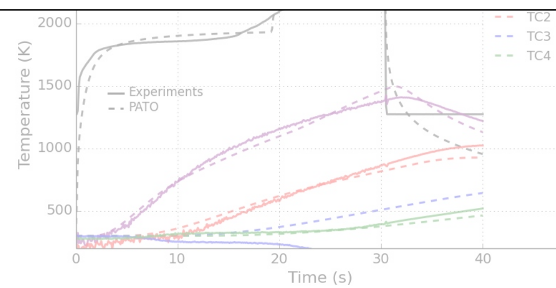
in arc
nodels

Posters on PATO:

Jeremie Meurisse – Arc jet CFD/ablation simulations using a plasma flow model in the arc heater

John Thornton – Coupling CFD and Material Response for Analysis of Mars Entry

Sergio Fraile Izquierdo – Mechanical Erosion Modeling of TPS Materials



CHAR – Charring Ablator Response Code

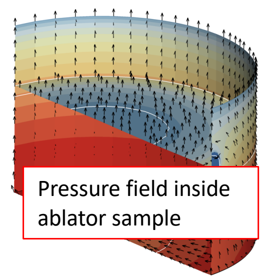
Principal NASA user base is in Orion and Commercial Crew Programs

- Vehicle design, ground testing, flight data analysis
- Licensed across industry only to US govt. contractors

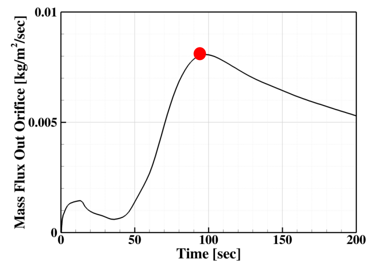
One-, two-, and three-dimensional direct and inverse unstructured finite element thermal and ablation solver

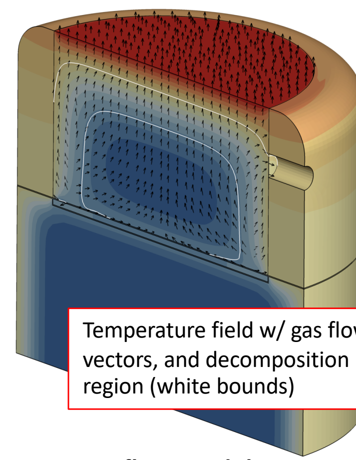
- NASA-led development with contributions from ATA Engineering and Corvid Technologies
- Rich suite of boundary conditions including surface-to-surface radiation exchange, contact interfaces, and multiphysics coupling (ATA led)
- Other features include adaptive mesh refinement, and coupled thermo-electric solver

Current development efforts include mesh motion, in-depth chemical non-equilibrium and condensation, mechanistic decomposition modeling, and automatic differentiation



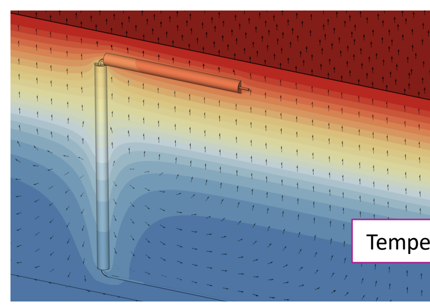
Pressure field inside ablator sample





Temperature field w/ gas flow vectors, and decomposition region (white bounds)

Pyro gas flow model validation arc jet test



Flight data analysis to determine thermal interference from thermocouple embedded in ablator

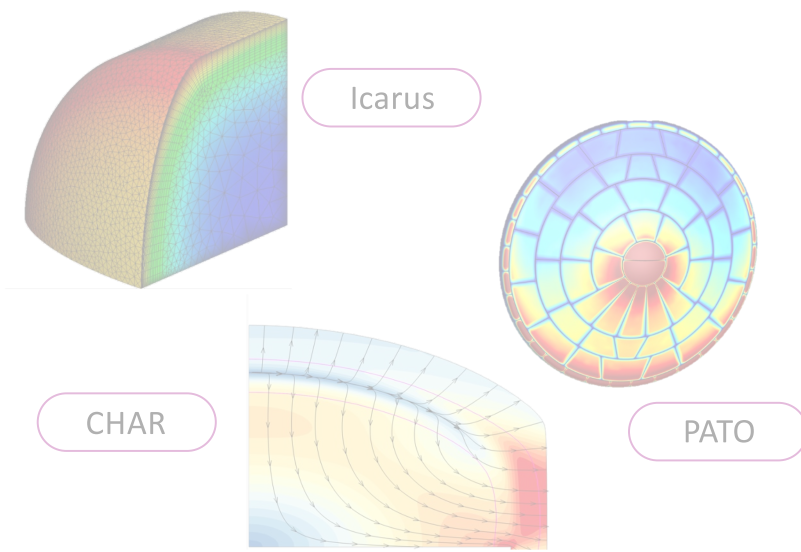
Temperature field with gas flow vectors

POCs: Amar, Cooper, Oliver

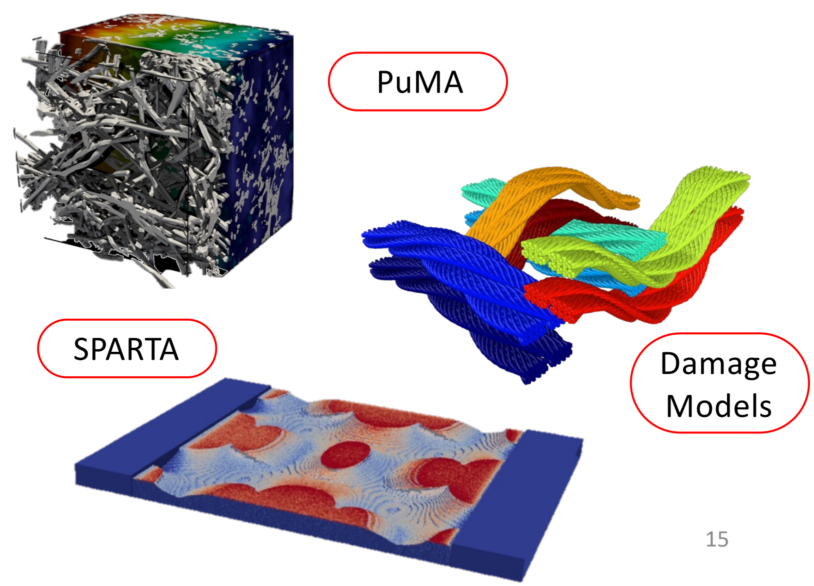
Research & Development Strategy

Recent investments in TPS ablation tool development focused on meeting challenges of flight projects – mediated by the Entry Systems Modeling (ESM) and flight projects

Modernizing Material Response Codes



Maturing Microscale Capabilities



PuMA – Porous Microstructure Analysis

Principal NASA user base is focused on improved characterization of TPS material properties

- Treats fibrous, woven, Avcoat-type, foam TPS
- Open distribution and a collaborative platform for interacting with industry/academia

Finite volume, microstructure-based property calculations

- NASA developed through ESM support
- Structures generated through micro-CT or artificially generated (woven, fibrous, etc)
- Properties computed include porosity, permeability, thermal conductivity, and elastic mechanical

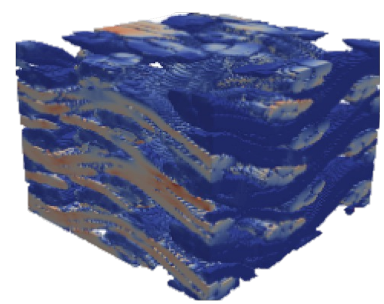
Current development efforts include extension to more complex thermo-mechanical properties and to treatment of emerging TPS materials (weaves, additively manufactured, etc)

NASA Software of the Year 2022!

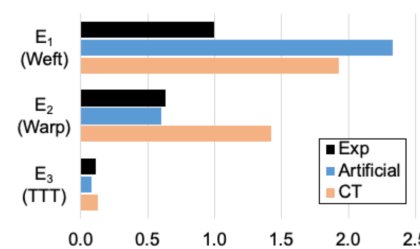
Micro-CT Scan

PATO used to analyze mechanical properties of woven TPS material for MSR-EES using micro-CT data

Stress Distribution



Normalized Young's Modulus



POCs: Fraile Izquierdo and Semeraro

PuMA – Porous Microstructure Analysis

Principal NASA user base is focused on improved characterization of TPS material properties

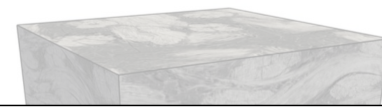
- Treats fibrous, woven, Avcoat-type, foam TPS
- Open distribution and a collaborative platform for interacti…

Finite volume… calculations

- NASA de…
- Structures generated through micro-CT or artificially generated (woven, fibrous, etc)
- Properties computed include porosity, permeability, thermal conductivity, and elastic mechanical

Current development efforts include extension to more complex thermo-mechanical properties and to treatment of emerging TPS materials (weaves, additively manufactured, etc)

Micro-CT Scan

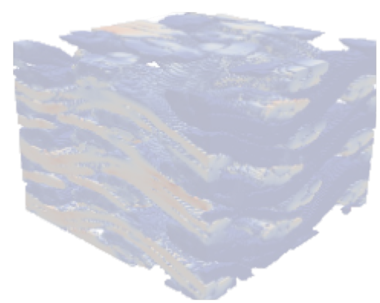


PATO used to analyze mechanical properties … aterial … ng

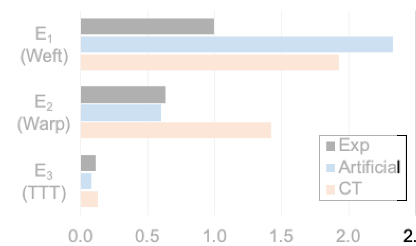
Posters on PuMA:

Federico Semeraro – Computing the effective elasticity of anisotropic porous media from X-ray computed micro-tomography images

Stress Distribution



Normalized Young's Modulus



SPARTA – Stochastic PArallel Rarefied-gas Time-accurate Analyzer

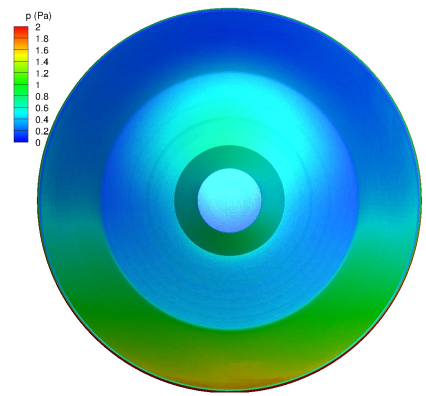
Principal NASA user base is focused on improved characterization of rarefied flows (surface and in-depth) and gas-surface interactions

- Evaluating surface pressure, stresses, and reaction rates
- Open distribution from SNL with select developments being limited distribution

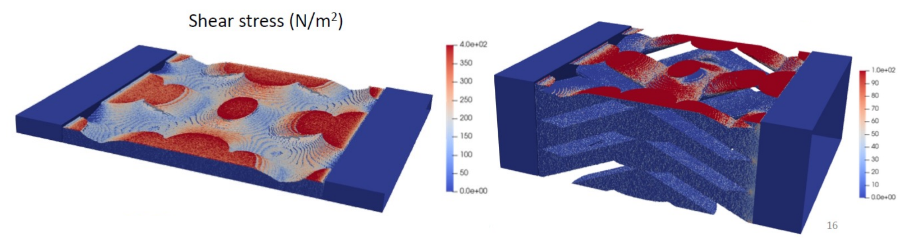
Direct simulation Monte Carlo solver

- Initiated at SNL, co-developed at NASA through ESM support
- Massively parallel and treated flow of billions of particles and grid cells
- Used to characterize flow, gas-surface collisions, finite-rate reactions, and recession in porous media

Current development efforts include extension to include oxidation influence on mechanical degradation of carbon materials and improving description of finite rate reactions



SPARTA used for accurate characterization of Mars2020 backshell and shear stress on woven TPS for MSR-EES to inform spallation



POCs: Swaminathan Gopalan and Borner

SPARTA – Stochastic PArallel Rarefied-gas Time-accurate Analyzer

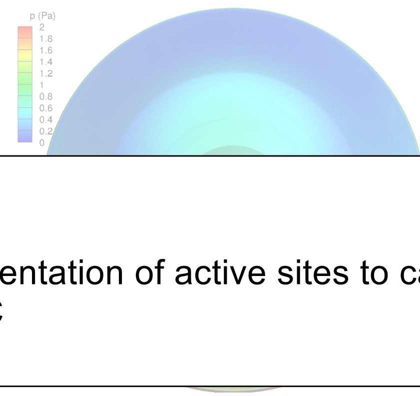
Principal NASA user base is focused on improved characterization of rarefied flows (surface and in-depth) and gas-surface interactions

- Evaluating surface pressure, stresses, and reaction rates
- Open dis… developr…

Direct simulat…

- Initiated … ESM sup…
- Massively parallel and treated flow of billions of particles and grid cells
- Used to characterize flow, gas-surface collisions, finite-rate reactions, and recession in porous media

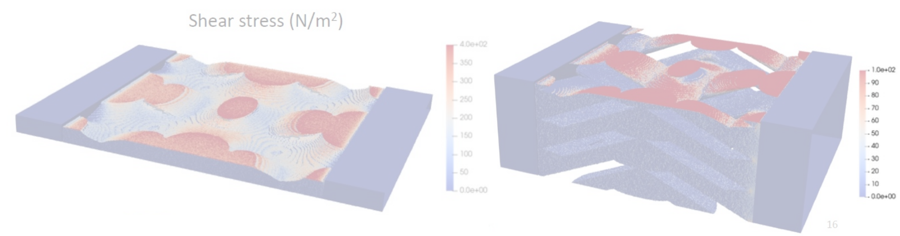
Current development efforts include extension to include oxidation influence on mechanical degradation of carbon materials and improving description of finite rate reactions



SPARTA used for accurate characterization of … backshell and … s on woven TPS … S to inform

Talk on SPARTA:

Krishnan Swaminathan Gopalan – Implementation of active sites to capture pitting of oxidizing carbon materials in DSMC



Damage Modeling

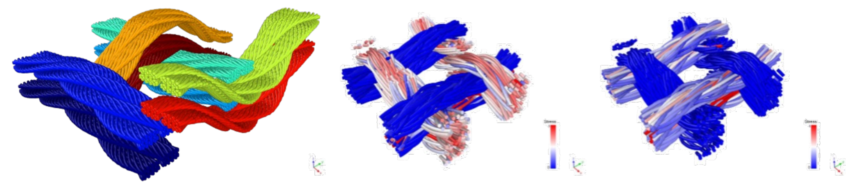
Lauren will talk about this

Principal NASA user base is focused on treatment of damage in woven TPS for MSR-EES

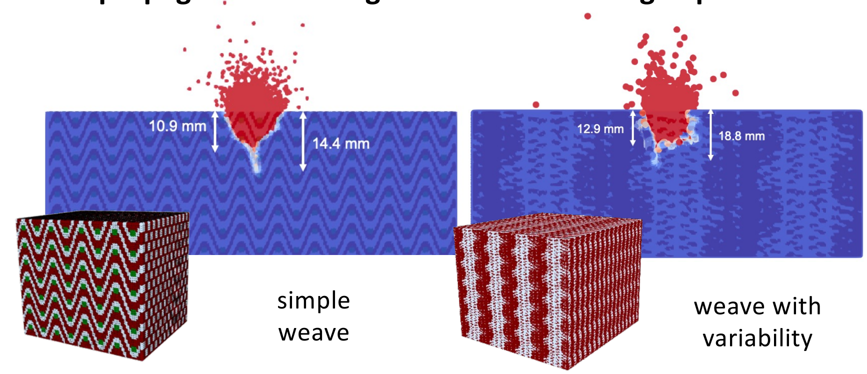
- Supported through ESM
- Investigating mechanical failure, damage influence on properties, and impact

Variety of codes in development to characterize damage progression and failure in TPS materials

- Code developments through ESM support
- LAMMPS – particle-based impact/crack propagation for MMOD damage and discrete element models of woven TPS
- NASMAT – cell-based approach for treatment of properties and progressive damage in TPS materials
- HYDRA – in-house code with specialized damage models for woven TPS materials



LAMMPS and HYDRA employed to study mechanical-mediated failure of weaves and the damage and propagation resulting from ballistic testing impacts



POCs: Abbott, Santos, Haskins

Damage Modeling

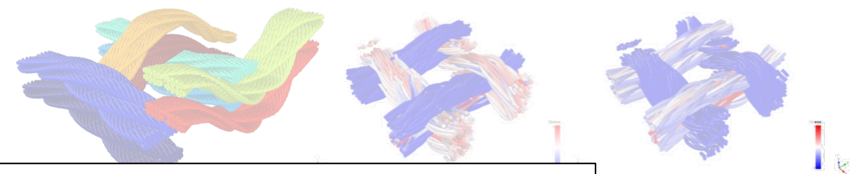
Lauren will talk about this

Principal NASA user base is focused on treatment of damage in woven TPS for MSR-EES

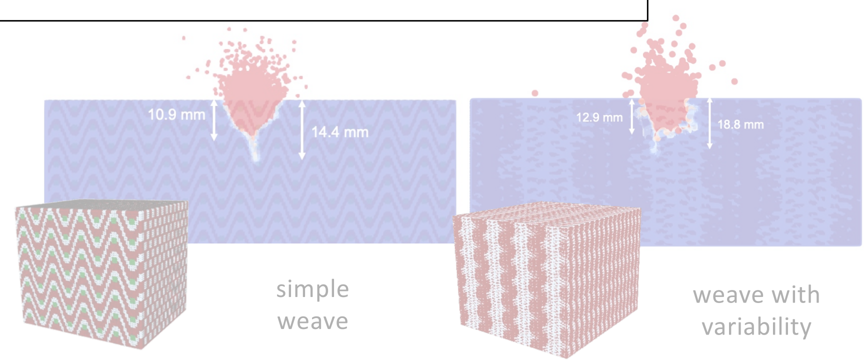
- Supported through ESM
- Investig…
  influenc…

**Variety of cod…
damage progr…**

- Code developments through ESM support
- LAMMPS – particle-based impact/crack propagation for MMOD damage and discrete element models of woven TPS
- NASMAT – cell-based approach for treatment of properties and progressive damage in TPS materials
- HYDRA – in-house code with specialized damage models for woven TPS materials



…echanical-
…ge and
… impacts



Talk on Property/Damage:

Lauren Abbott – TPS certification by analysis: model-driven characterization of properties and failure in woven TPS

University Partnership Highlights

NASA Space Technology Research Institute (STRI)

Advanced Computational Center for Entry Systems Simulation (ACCESS)

Five-year institute dedicated to advancing the computational state-of-the-art of entry systems simulations. Four main thrusts investigated by a consortium of universities:

- Iain Boyd, Director (CUB)
- Alexandre Martin, TPS Lead (UK)
- Marco Panesi, Kinetics & Flow Physics Lead (UIUC)
- Graham Candler, Integration Lead (UMN)
- Alireza Doostan, UQ & Reliability Lead (CUB)

NASA Center-Specific Summer Internship Programs

ARC regularly hosts 20-40 summer interns focused on entry systems

NASA Space Technology Graduate Research Opportunity (NSTGRO)

10+ current students at Stanford, UIUC, CUB, UK, and UMN with focuses ranging from dust erosion to influence micrometeoroid impact on ablative response

Early Career Faculty (ECF) / Early Stage Innovations (ESI)

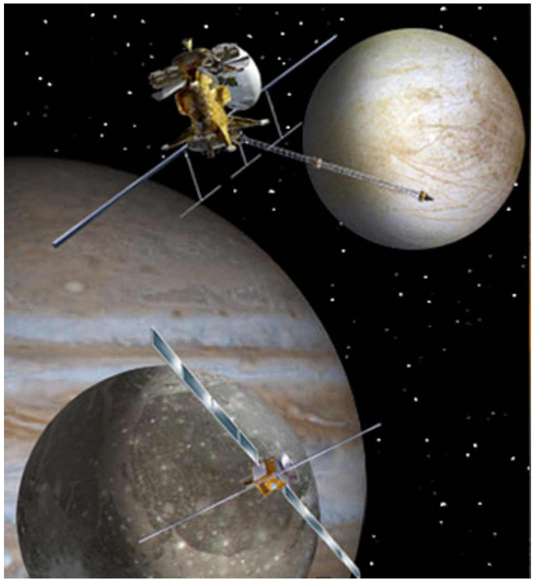
- Enhanced Diagnostics for Characterizing Entry Aerothermal Environments in High-enthalpy Impulse Facilities (Purdue, UCLA and University of Virginia)
- Modeling Shock Layer Radiation and Chemical Kinetics for Planetary Entry (Montana State University and University of Illinois Urbana Champaign)

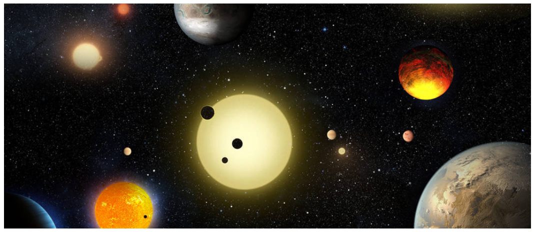
NASA Established Program to Stimulate Competitive Research (EPSCoR)

Kentucky EPSCoRs have been awarded on topics ranging from better characterizing TPS radiation response to design, manufacture, and entry testing of probes (KRUPS/KREPE)

Takeaways

- Strategy of modernizing macroscale and maturing microscale ablation modeling tools
- Developed tools addressing entry challenges of slated flight projects/missions
- Robust network of universities providing fundamental developments and talent pipeline
- Future challenges include preparing tools to treat aggressive entry scenarios associated with outer planet missions





Questions?