Space Technology Mission Directorate
Game Changing Development Program

Justin Haskins and Aaron Brandis | Tom West | FY23 Entry Systems Modeling Annual Review Presentation | 09.21.23
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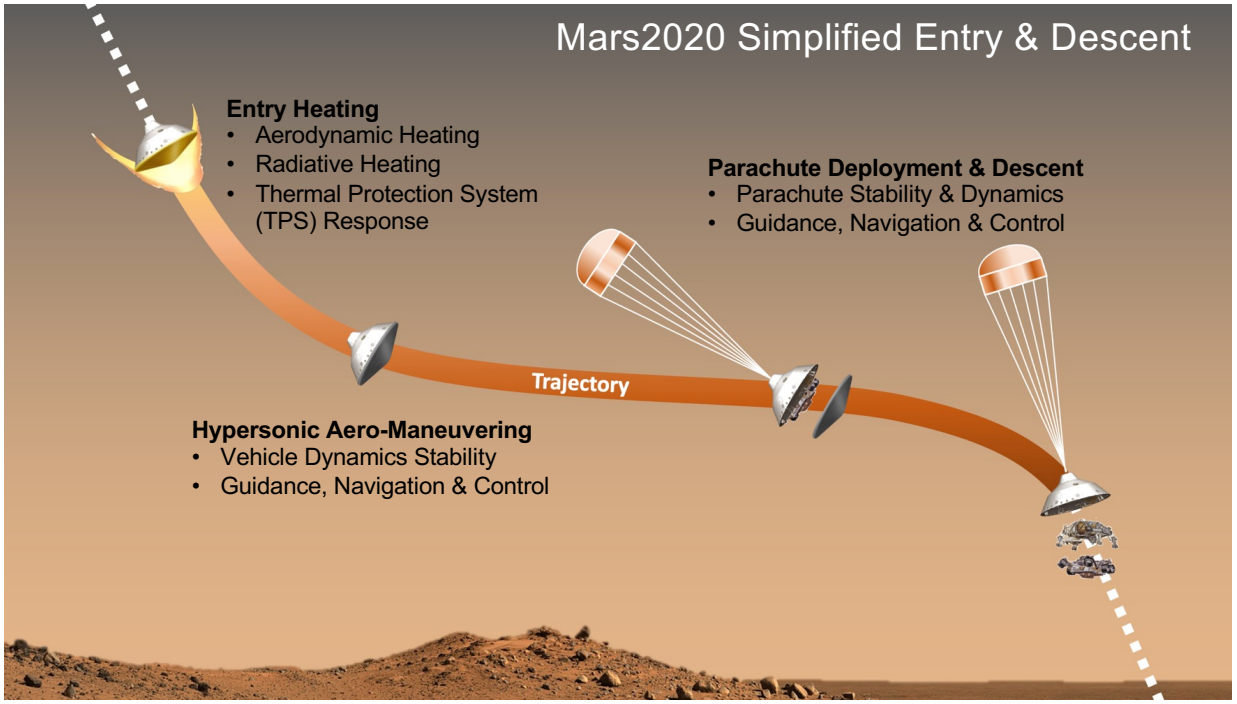
Challenges for Entry, Descent, and Landing (EDL)

EDL comprises a relatively small portion of a mission's timeline, however, it is typically among the largest risks. Flying through a body's atmosphere reliably and accurately – from orbit to ground or via aerocapture – is a critical step toward successful in situ exploration.

- EDL is a multi-stage process that can be unique to a given mission and destination
- Each stage presents challenges – high velocity, large thermal gradients, and complex maneuvers
- Ground testing does not provide comprehensive data on EDL – validated models required for ground to flight traceability



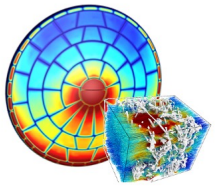
Entry Systems Modeling (ESM)
Project Overview

Technology Capability Product: cross-cutting tools and technologies for modeling entry systems that improve performance, reduce mission risk, and enable new system capabilities across the Solar System

Technical Capability: consists of *five technical capability areas* & *three new starts*

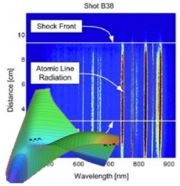
Technical Capability Areas

TPS Materials Modeling



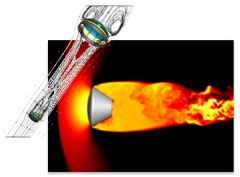
multiscale models of TPS material reliability and performance

Shock Layer Kinetics & Radiation



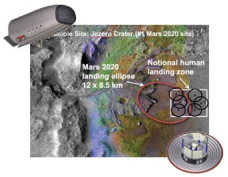
high-temperature gas physics of entry systems from quantum to engineering scales

Aerosciences



parachute dynamics, vehicle dynamics & stability, turbulent heating, advanced numerical methods

Guidance, Navigation & Control



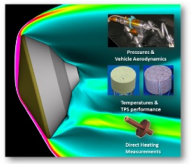
end-to-end simulation capability for multiple mission EDL concepts of operation

Ground Test Validation

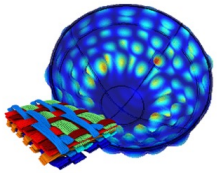
ground testing to support uncertainty quantification – unique facilities and diagnostics

New Starts

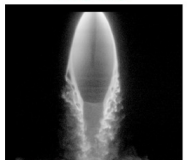
MEDLI2 Deep Dive



TPS Certification by Analysis



Hypersonic Wake Flows



Project Overview

- Goals and objectives map to five technical capability areas – will be updates for the next project cycle
- Objectives address a wide range of technology needs – 18 of 76 EDL Capability Gaps

Project Goals	
Goal #1	Produce high-fidelity TPS material models to reduce mission risk and improve design reliability
Goal #2	Develop physics-driven models of high-temperature gas chemistry and radiation relevant to EDL missions
Goal #3	Develop tools for simulating complex, unsteady aerodynamic phenomena
Goal #4	Create end-to-end simulation capability for multiple mission EDL concepts of operation
Goal #5	Deliver tools & capabilities to stakeholders with quantified uncertainty models

Project Objectives	
Objective #1	Develop and validate next-gen PATO, Icarus, PuMA, and SPARTA codes for multiscale material modeling
Objective #2	Generate comprehensive chemistry and radiation databases for all Solar System EDL targets using computational chemistry and testing in the Electric Arc Shock Tube
Objective #3	Develop and validate next-gen CFD methods for analysis of unsteady flows: wake flows, jet interactions, vehicle dynamics, parachute dynamics, high order numerical schemes
Objective #4	Implement multi-threading in POST2 simulation and develop interoperability framework to couple with external applications

ESM Organizational Chart

Science Mission Directorate

PESTO Program Manager– E. Montbach

Space Technology Mission Directorate

GCD Program Element Manager – W. May
EDL Systems Capability Lead – M. Wright

Entry Systems Modeling Project

Project Manager	**Principal Investigator**
PjM – J. Haskins (ARC) DPjM – M. Hughes (LaRC)	PI – A. Brandis (ARC) DPI – T. West (LaRC)

Scheduler – L. Campbell (LaRC)

Resources – J. Henegar (LaRC)

TPS Materials
- Predictive Material Modeling
- Coupled Material Response
- TPS Characterization Suite

Shock Layer Kinetics & Radiation
- Radiation Model Development
- Electric Arc Shock Tube

Aerosciences
- Mission Relevant Roughness
- Parachute FSI
- Advanced Numerical Methods
- Free-Flight CFD
- Magnetic Suspension Wind Tunnel

Guidance, Navigation & Control

TPS Certification by Analysis

Hypersonic Wake Flows

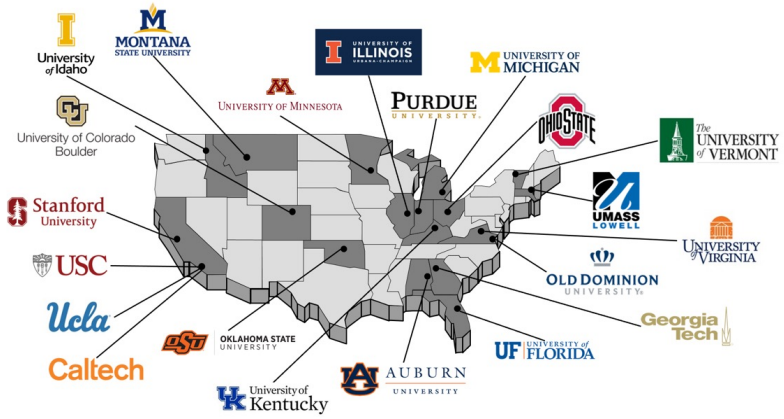
MEDLI2 Deep Dive

Collaborations & Partnerships

ESM is a successful, multi-year collaboration between ***STMD*** and ***SMD***

Centers	***Universities***	***OGA***	***International***	***SBIR/STTR***
Ames Langley Johnson Glenn	21+ Institutions NASA/ESM Grants 25 Institutions through NSTGRO	Air Force Office of Scientific Research Office of Naval Research Missile Defense Agency Sandia National Laboratory Lawrence Berkeley National Laboratory Lawrence Livermore National Laboratory	German Aerospace Center Ecole CentraleSupelec Von Karman Institute University of Queensland *Oxford University* Instituto Superior Tecnico *European Space Agency*	Corvid Technologies

Universities with NASA/ESM Grants



Exploration & Science Applicability

- Orion *[Ongoing]*
- Mars 2020 *[Completed]*
- Mars Sample Return – Earth Entry System and Sample Retrieval Lander *[Ongoing]*
- Dragonfly *[Ongoing]*
- DAVINCI *[Potential]*
- STMD technology projects: e.g., MEDLI2, LOFTID, and others as warranted

Education/Public Outreach
Summary – Publications, Grants & Academia

- Over 85 publications* and/or presentations; highlights include:

Date	Papers/Posters/Panel Discussions	Number of Papers/Posters/Panel Discussions
Oct 2022	Ablation Workshop	12
Jan 2023	AIAA SciTech 2023	35
Feb 2023	NASA TM	2
Multiple	Journal Entries	7
Jun 2023	AIAA Aviation 2023	13
Aug 2023	IPPW Conference Presenter	6

- 7 Established International Agreements, 2 more in process
- 29 Grants*; highlights include:
  - 1 NASA Space Technology Research Institute
  - 7 funded by ESM
  - 13 ECF/ESI with oversight/collaboration from ESM
  - 7 funded by EPSCoR program with oversight/collaboration from ESM
- 62 Students*; highlights include:
  - NSTRF/NSTGRO: ESM Team Members are Research Collaborators for 25 Interns
  - Supporting 2 Pathways students
  - Supporting 3 Post-docs
  - Supporting 10 students through ESI 2022

* Raw data recorded in tables in Backup

Education/Public Outreach
Summary – Awards & Press Releases

➢ Awards

- Former ESM project manager, Michael Wright, NASA Ames Research Center, was selected for the 2023 AIAA Thermophysics Award.

Citation: For outstanding contributions to improving thermophysical models and simulation capabilities for high-enthalpy flows, and for leadership and dedication to NASA missions and the aerothermodynamic community. (Jun 2023)

- Multiscale Progressive Failure Analysis of 3D Woven Composites Journal Article Received Best Paper Award in the 2022 Materials and Structures Division at GRC (Apr 2023)

➢ Newsworthy

- Article released on NASA.gov highlighting the Wake Flow Planar Laser Induced Fluorescence (PLIF) experimental measurement technique for heat shield development: https://www.nasa.gov/feature/experimental-measurement-technique-for-heat-shield-development
- ESM Participation in the NASA Langley/Ames EDL Summer Seminar Series for Summer Interns
- Public Release of the MPEC Software (Jun 2023)
- Special Session on Entry Systems Modeling, AIAA SciTech 2023

Upcoming Events: 6 Month Look-Ahead	
ESM Workshop	October 2023
AIAA ASCEND	October 2023
VEXAG	October 2023
Ablation Workshop	November 2023
SC23	November 2023
OPAG	November 2023
AIAA SciTech	January 2024

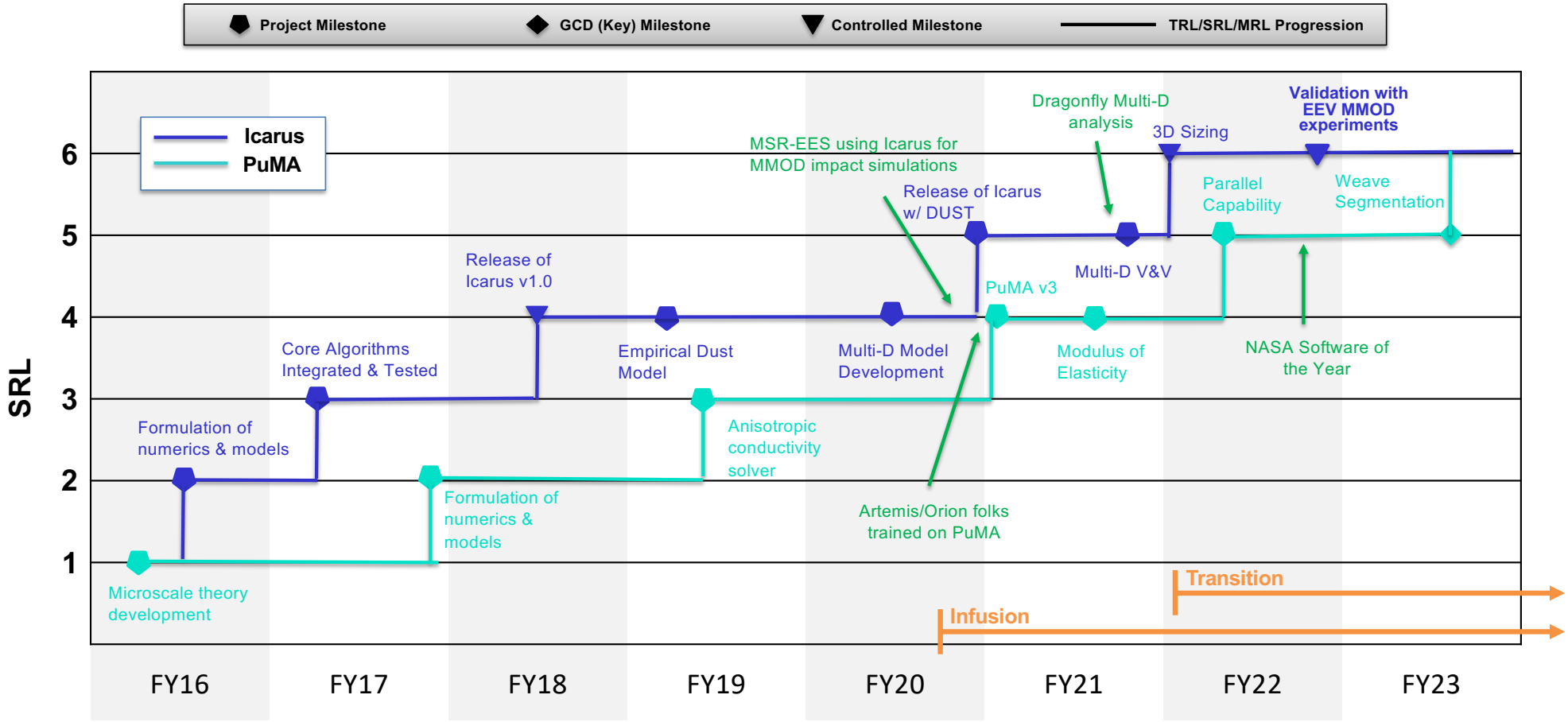
* Raw data recorded in tables in subsequent charts

Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					**Schedule** – Langley HyMETS Arc Jet facility issues have created schedule pressure for MEDLI2 Deep Dive testing and analysis of Mars2020 heatshield material samples. A subset of samples will be sent to University of Illinois Urbana-Champaign for testing in the new Plasmatron-X facility, which could remediate schedule pressure if successful.
Annual					**Schedule** – Langley HyMETS Arc Jet facility issues persist, but the University of Illinois Urbana-Champaign Plasmatron-X testing was successful and provided sufficient data to meet MEDLI2 Deep Dive goals and close-out criteria.

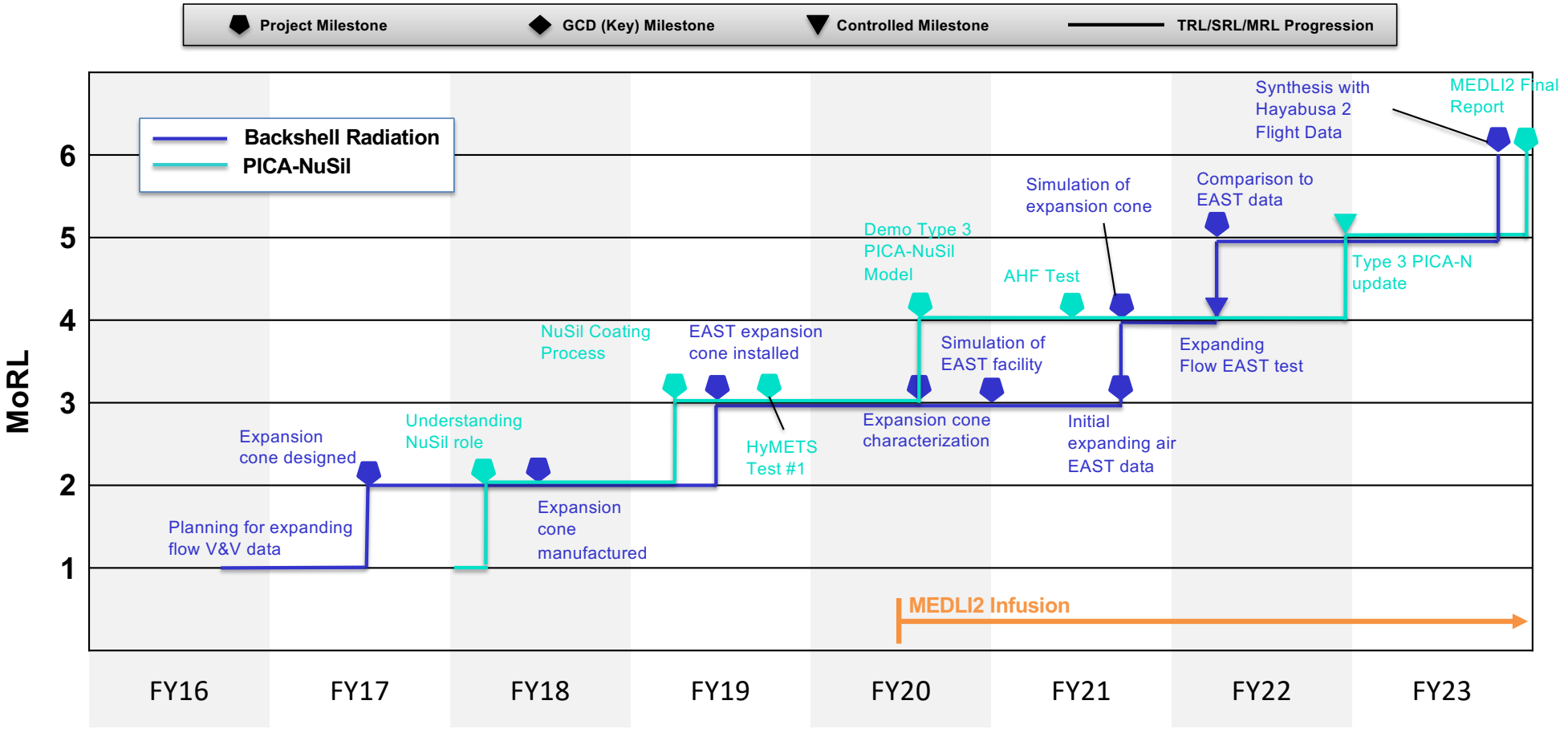
Example ESM Software Development

Icarus and PuMA



Example ESM Model Development

Backshell Radiation and PICA-NuSil

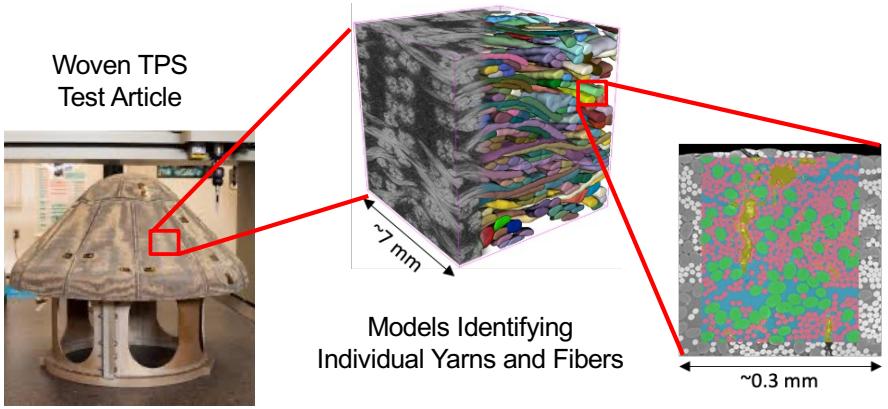


Accomplishments
TPS Certification by Analysis

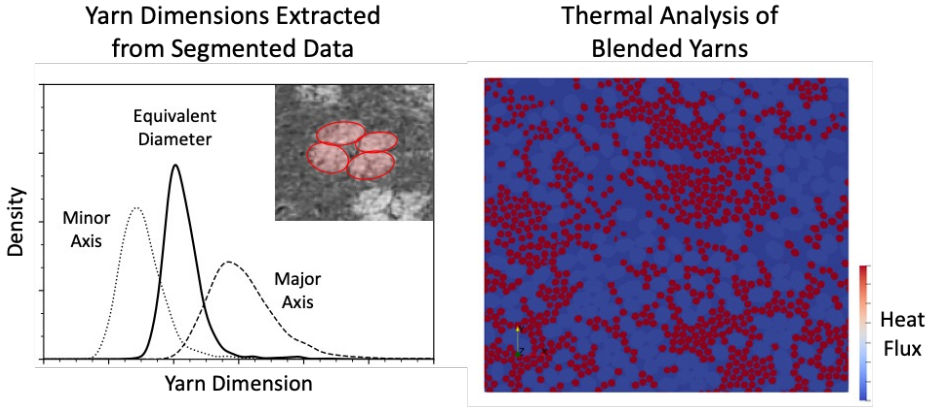
Advanced Woven Thermal Protection Materials Analysis

- Structural Variability – improved understanding of woven TPS structure using machine learning interpretation of microscale imaging such as X-ray computed tomography (micro-CT)
- Property Variability – improved bounds on mechanical strength and thermal properties using multiscale material analysis with image informed models

Machine Learning Segmentation



Characterization of As-Manufactured Materials

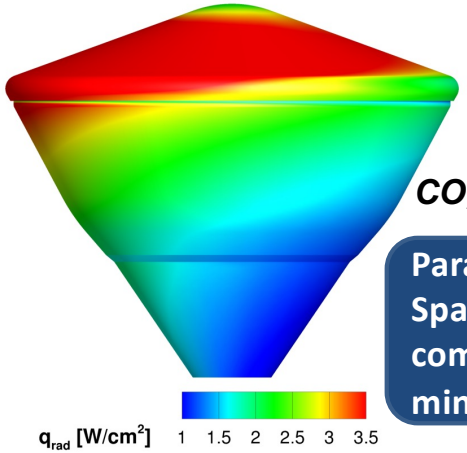


Results inform risk reduction due to material variability and qualify woven TPS for MSR-EES

Accomplishments
New Aerothermal Tools

NERO

- NERO is a new radiation solver that delivers 2-3 orders-of-magnitude speed-up for radiative heating calculations. *[Technical first]*
- Enables rigorous analysis of aeroshell heating while accounting for complex features, which translates into improved TPS sizing.
- Efficacy demonstrated on a diverse set of flight problems including the MSR Sample Retrieval Lander and Dragonfly.



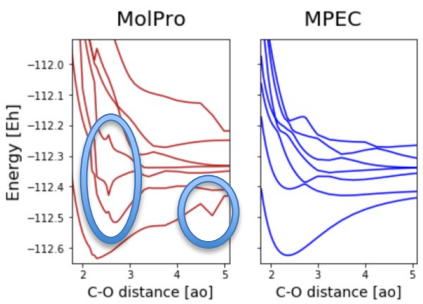
CO_2 + CO IR Radiation for SRL

Paradigm shift:
Spacecraft simulations with complex body features require minutes instead of hours/days.

MPEC

- MPEC is a new tool to calculate molecular electronic structure.
- The motivation for MPEC is to perform calculations beyond the limitations of the established heritage tool, Molpro
- Upcoming work using MPEC will focus on providing CN radiative heating insights relevant to Dragonfly.

CO^+ calculations enabled by MPEC



unphysical discontinuities with old method

better convergence in challenging systems

New Start-of-the-Art:
Enable quantum chemistry larger problem types relevant to NASA.

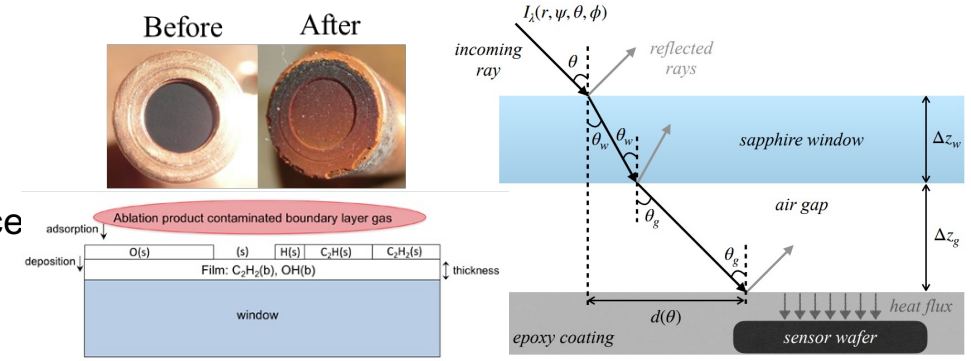
Accomplishments
MEDLI2 Deep Dive

ENTRY SYSTEMS MODELING

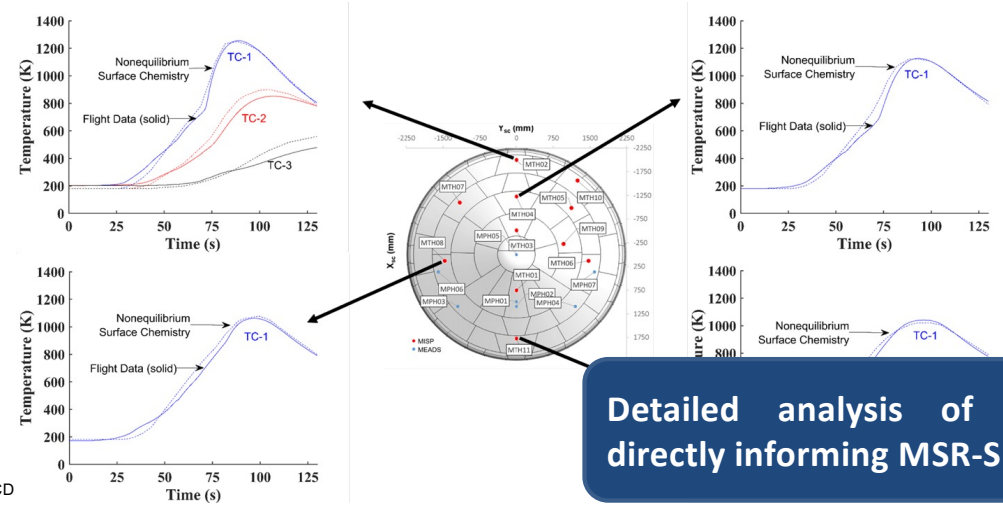
➢ FY23 Technical Achievements

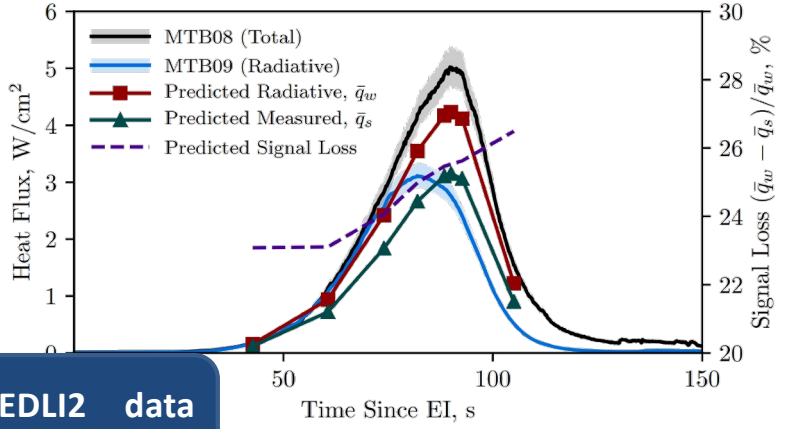
- ➢ Enhancements in understanding MEDLI2 radiometer through improved optics and ablation product deposition modeling
- ➢ Unprecedented level of agreement between near-surface temperature predictions using detailed surface chemistry

Radiometer Optics and Ablation Product Deposition



Analysis for Near-Surface Thermocouples





Detailed analysis of MEDLI2 data directly informing MSR-SRL TPS design.

On-going study defining how best to interpret flight radiometer data

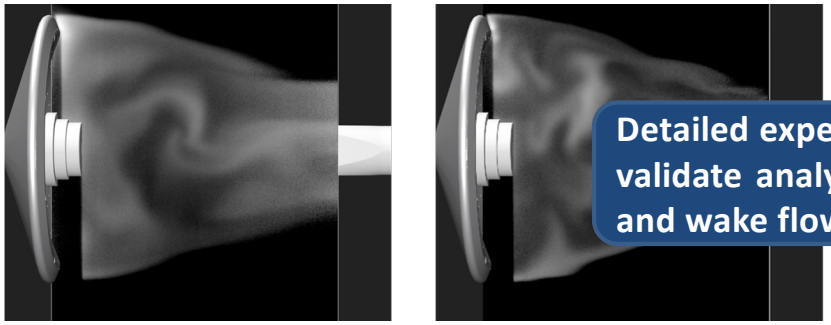
Accomplishments
Wake Flows

➢ Experimental Wake Analyses

- ➢ Completed two wake flow tests at LaRC 31" Mach 10 Tunnel on LOFTID-relevant geometry using planar laser-induced fluorescence (PLIF) and Femtosecond Laser Electronic Excitation Tagging (FLEET) tests
- ➢ Initial data processing for both tests have been completed and information used to improve techniques for future testing

Hypersonic Wake Flow PLIF Visualization

Increasing Freestream Reynolds Number

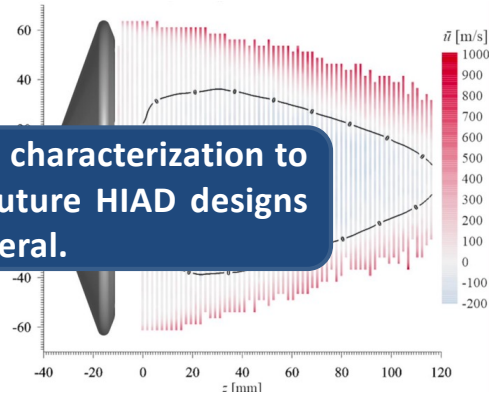


$Re_\infty/L = 1.8x10^6\ m^{-1}$ $Re_\infty/L = 6.3x10^6\ m^{-1}$

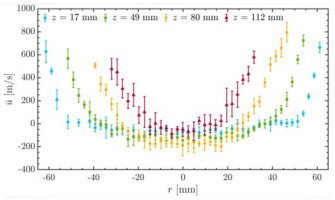
Detailed experimental characterization to validate analysis for future HIAD designs and wake flows in general.

Hypersonic Wake PLIF Velocimetry

Streamwise Velocity



Spanwise Velocity

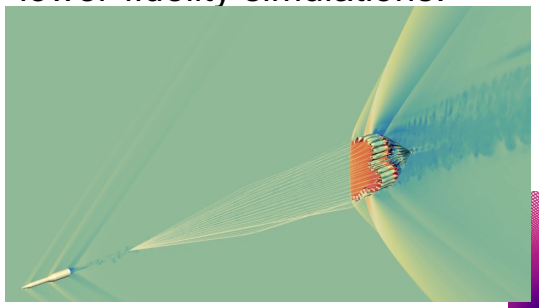


Molecular tagging velocimetry for streamwise velocity (Δt = 500 ns) using 1D diffractive optical element

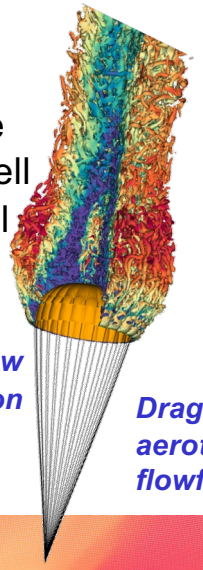
Mission Transition & Infusion

Parachute Modeling

Excellent agreement shown with ASPIRE parachute flight test. Increased confidence leading to begin work on a drogue-aeroshell simulation for **Dragonfly & MSR-SRL**. Will provide insights into dynamics and anchor lower-fidelity simulations.



LAVA ASPIRE FSI simulation



FSI flow visualization

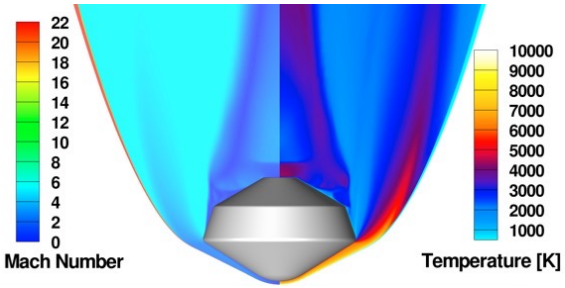
Dragonfly Free-Flight simulation

Dynamic stability

Free-Flight simulation capability a critical tool used to understand the passive entry vehicle dynamic stability of **MSR-EES & Dragonfly**.

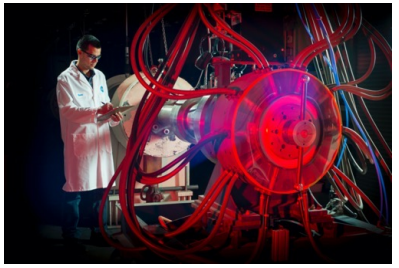
Titan Aerothermal Environments

ESM anticipated need in advance of a Titan mission with EAST shock tube test. Enabled informed margin policy and improved models to be used by **Dragonfly** – neither would have been possible without this data.



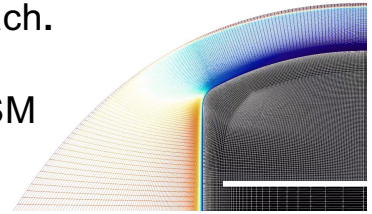
Dragonfly aerothermal flowfield

EAST Shock Tube



Multi-Dimensional Response

Dragonfly & MSR-EES have some complicated geometries that cannot be modeled with traditional 1-D approach. Coupled multi-dimensional material response tools developed within ESM being utilized.

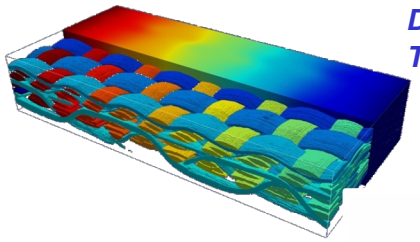


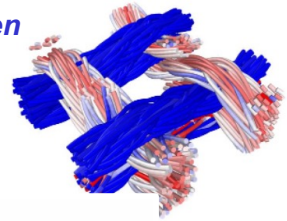
3D Ares simulation of recessing Arc Jet coupon

Mission Transition & Infusion

TPS Cert for Orion

TPS Certification tools have shown so much promise, already being infused by **MSR-EES** to characterize the new class of woven TPS materials and provide insights into the **Orion/Artemis-1** heatshield performance.





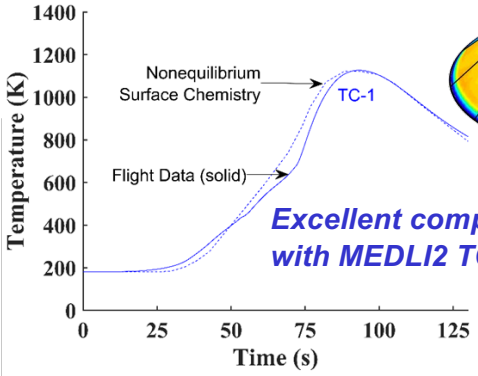
Developing woven TPS models

Simulation of tiled MSL heatshield

NuSil coated PICA

MEDLI2 Deep Dive (NuSil) detailed analysis provided supporting evidence to inform change of **MSR-SRL** TPS design process.

(* SRL design decisions made by them, not ESM)

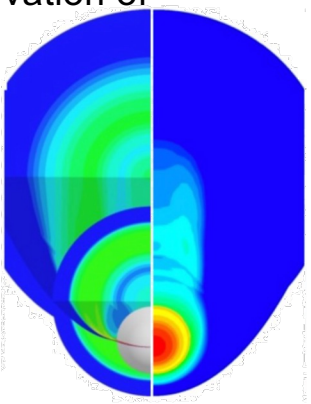


Excellent comparison with MEDLI2 TC data

Radiative Heating In Flight

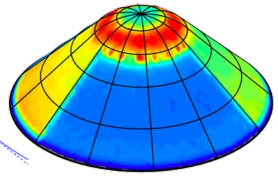
ESM responsible for characterization, calibration and analysis of the **Orion** radiometer and spectrometer. Tools showed excellent agreement with observation of **Hayabusa-2** return.

Hayabusa-2 entry simulated

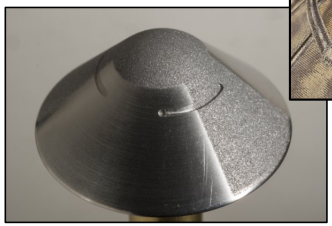


Roughness Margin for EES

MSR-EES margin & nominal environment due to TPS roughness augmented heat flux derived from need-anticipating ESM testing.



Augmented heating measured



HEEET Engineering Test Unit & range model

ESM FY25+
New Project Objectives & Future Milestones

1. Develop and validate next-gen multiscale simulation of TPS materials, modeling of complex TPS configurations, and provide capability to assess fracture and failure of TPS.

- Refined model for NuSil and other coatings
- Investigate anomalous TPS material behavior
- Strong coupling of flow & material response
- Informing manufacturing and material reliability

2. Generate comprehensive chemistry and radiation databases for all Solar System EDL targets using computational chemistry, shock tube testing and reconstruction of flight data.

- Extend NERO & MPEC verification for mission application
- Venus & Gas Giants EAST shock tube campaign
- Artemis/Orion spectrometer analysis
- Framework for automated synthesis of kinetic data

3. Develop and validate next-gen CFD toolchain with emphasis on: High-resolution, unsteady flow phenomena; Entry vehicle dynamics; Parachute dynamics; High-order numerical schemes; HPC acceleration.

- Further LAVA parachute capability / parametric analysis
- Roughness augmented heating model development
- Aerodynamic model formulation for vehicle dynamics
- Production-ready scale-resolving simulation capability

ESM FY25+
New Project Objectives & Future Milestones

4. Develop and demonstrate performance of robust guidance and control schemes for precision landing and aerocapture. Integrate with UQ-in-the-loop to enable real-time trajectory optimization.

- End-to-end atmospheric and exo-atmospheric trajectory analysis
- Development of GNC test architecture for novel guidance schemes
- UQ optimized guidance schemes

5. Perform system-scale sensitivity studies of EDL toolchain applied to missions of record in order to identify and prioritize technical gaps. Integrate UQ throughout workflow.

- Multi-Physics Coupling
- Formulate physics-informed neural nets for integrated EDL analysis
- EDL Aeroshell design under uncertainty

Summary

➢ Project performance

- Budget management was very challenging under CR – ESM still managed to attain >98% obligation of funds
- 11 key and controlled milestones completed in FY23 - Additional 7 expected to complete at end of this month
- NASA facility issues created schedule pressure requiring rephasing of certain activities
  - Some delays were mitigated by leveraging university partner facilities (University of Illinois Urbana-Champaign Plasmatron-X facility)

➢ Outreach & Recognition

- 85+ publications in FY23 ***(Best Paper Award at GRC)***
- 2023 AIAA Thermophysics Award (Mike Wright)
- 60+ students supported through internal project support and NASA programs
- 45+ university collaborations through internal project support and NASA programs

➢ Established and Strengthened Partnerships

- Mars Sample Return: Earth Entry Systems and Sample Return Lander
- Dragonfly
- Orion/Artemis 1
- Imminent: New Space Act Agreement signed with the European Space Agency (ESA) to study Outer Planets