ACCESS

NASA Space Technology Research Institute

Iain D. Boyd, Director

What is an Entry System?

- **An Entry System comprises all outer surfaces of a vehicle during its initial hypersonic interaction with an atmosphere and provides**
  - Structural integrity against aerodynamic loads
  - Thermal protection against heating loads

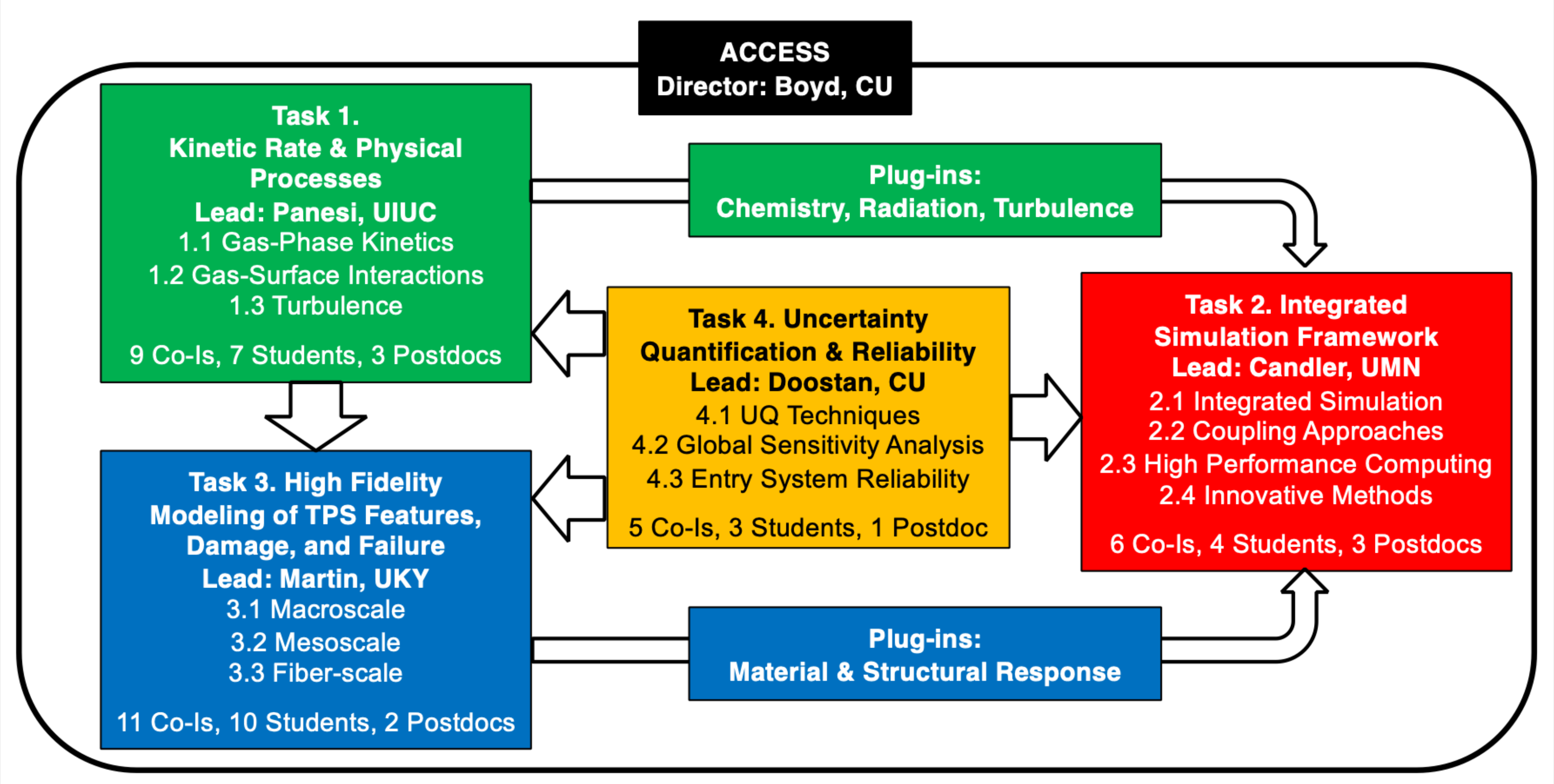
- **Entry System design considerations**
  - Hypersonic flow: chemistry, radiation, turbulence
  - Material response: conduction, radiation, surface chemistry (ablation), in-depth chemistry (pyrolysis)
  - Structural response: fracture, failure
  - Approach: minimize mass and provide margin
  - Industry uses a combination of analysis, testing, and legacy experience
  - NASA usually performs the high-fidelity analysis of flow and material response processes

ACCESS:
Vision & Objectives

- **Vision Statement**
  Revolutionize the analysis and design of planetary entry systems through development of a fully integrated, interdisciplinary, simulation capability employing high fidelity, validated physics models, including uncertainty quantification (UQ) and reliability, that is enabled by high performance computing

- **Primary Research Objectives**
  1. Integrated entry system analysis framework
  2. UQ and reliability for complex entry systems
  3. High fidelity models for flow physics, material and structural response incorporating UQ
  4. Execution on peta/exa-scale architectures

Institute Structure



ACCESS
Director: Boyd, CU

Task 1.
Kinetic Rate & Physical Processes
Lead: Panesi, UIUC
1.1 Gas-Phase Kinetics
1.2 Gas-Surface Interactions
1.3 Turbulence

9 Co-Is, 7 Students, 3 Postdocs

Plug-ins:
Chemistry, Radiation, Turbulence

Task 4. Uncertainty Quantification & Reliability
Lead: Doostan, CU
4.1 UQ Techniques
4.2 Global Sensitivity Analysis
4.3 Entry System Reliability

5 Co-Is, 3 Students, 1 Postdoc

Task 2. Integrated Simulation Framework
Lead: Candler, UMN
2.1 Integrated Simulation
2.2 Coupling Approaches
2.3 High Performance Computing
2.4 Innovative Methods

6 Co-Is, 4 Students, 3 Postdocs

Task 3. High Fidelity Modeling of TPS Features, Damage, and Failure
Lead: Martin, UKY
3.1 Macroscale
3.2 Mesoscale
3.3 Fiber-scale

11 Co-Is, 10 Students, 2 Postdocs

Plug-ins:
Material & Structural Response

NASA TPOC = Dr. Eric Stern (NASA-ARC)

Institute Members

University of Colorado (CU)
- Iain Boyd (Director, Tasks 1, 4)
- Alireza Doostan (Task 4 Lead)
- Dave Marshall (Task 3)
- Tim Minton (Task 1)
- Robyn Macdonald (Task 1)

University of Illinois (UIUC)
- Marco Panesi (Task 1 Lead, Task 4)
- Harley Johnson (Task 3)
- Francisco Panerai (Tasks 1, 3)
- Kelly Stephani (Tasks 1, 3)

University of New Mexico (UNM)
- Hua Guo (Task 1)

University of Maryland (UMD)
- Christoph Brehm (Task 1)

University of Kentucky (UKY)
- Alexandre Martin (Task 3 Lead, Task 4)
- Matthew Beck (Task 3)
- Hailong Chen (Task 3)
- Jack Maddox (Task 3)
- Savio Poovathingal (Task 3)

University of Minnesota (UMN)
- Graham Candler (Task 2 Lead, Task 4)
- Bernardo Cockburn (Task 2)
- Joseph Nichols (Task 2)
- Tom Schwartzentruber (Task 1)

***University of Oxford**
- Matt McGilvray (Task 1)

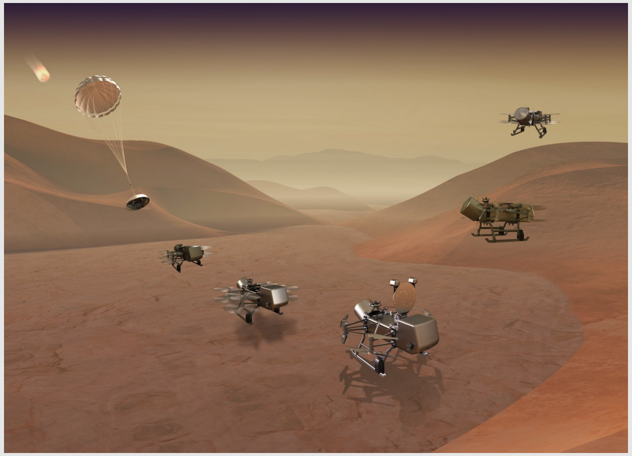
***National Research Center - Bari**
- Vincenzo Laporta (Task 1)

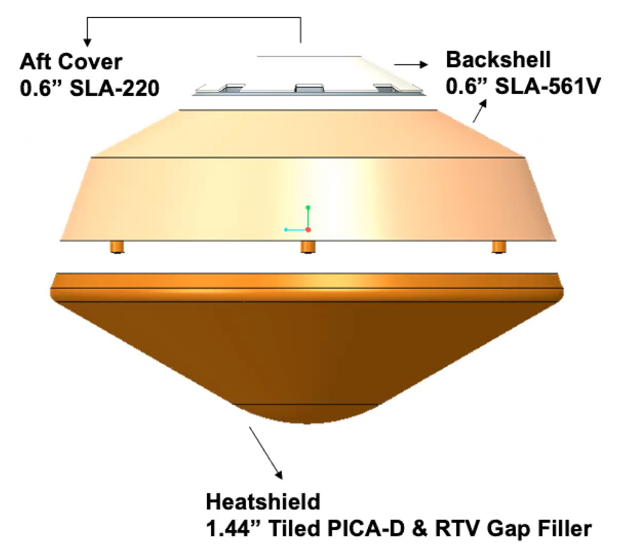
***Instituto Superior Tecnico - Lisbon**
- Mario Lino da Silva (Task 1)

*Unfunded participants

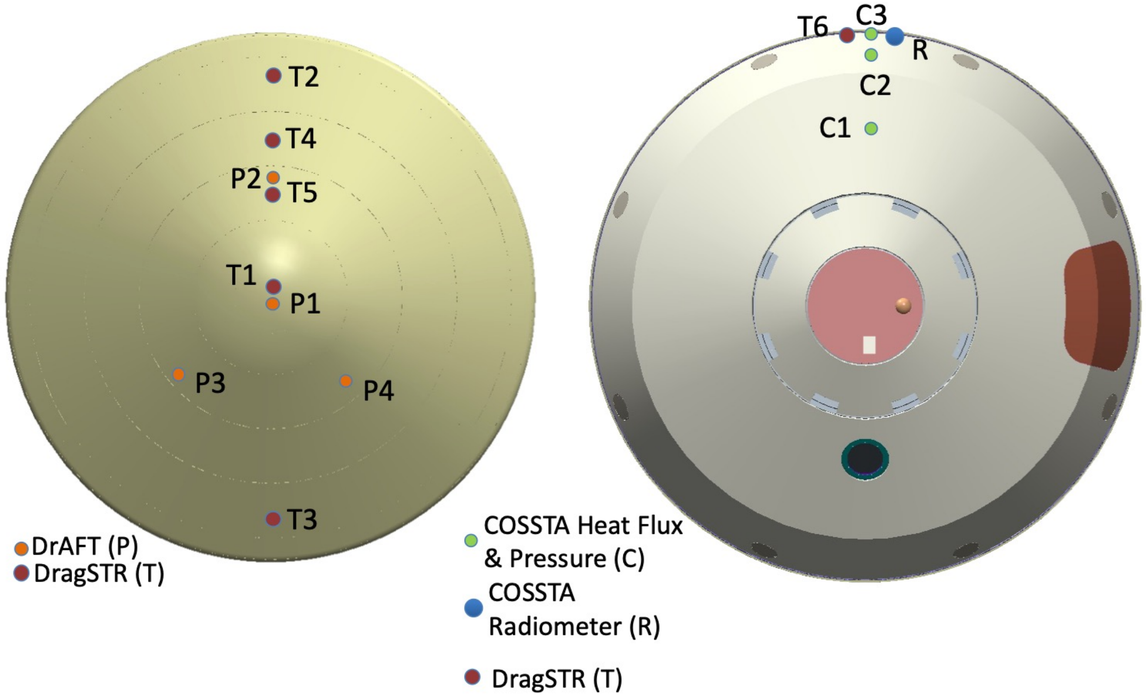
Exemplar Project-1:
Dragonfly (Years 1-2.5)

- Entry Mission
  - Deliver large rotorcraft to Titan surface
- Entry Environment:
  - 7.3 km/s, relatively long entry
  - Titan atmosphere: 98% N_2, 2% CH_4
- Entry System
  - Heatshield TPS = PICA-D with RTV
  - Backshell TPS = SLA-561V
- Key technical considerations
  - CN radiation up to 50% of total heating
  - Heat soak due to long entry
  - Lack of oxygen likely excludes ablation
  - Effects of pyrolysis products
  - Instrumentation package (DrEAM)
  - Turbulence due to surface roughness





Dragonfly:
DrEAM Instrumentation



- C1,C2,C3 each have two narrow band radiometers (for CN violet and CN red) and total heat flux
- C3 close to the aft shoulder
- C2 mid-point forward conic section
- C1 mid-point aft conic section

- CN Violet narrow band radiometer: 320 – 420 nm
- CN Red narrow band radiometer: 600 – 1800 nm

Focus Areas
During Dragonfly Project (Yrs 1-2.5)

1. Post-flight reconstruction of CH_4 atmospheric content [Task 1.1]
- Sensitivity analysis, computational chemistry, shock tube experiments

2. Assess influence of nitridation and pyrolysis products [Task 1.2]
- Compare finite rate surface chemistry model to B' tables
- Measure pyrolysis products, propagate from surface in CFD

3. High fidelity modeling of turbulence from rough surface [Task 1.3]
- Apply WM-LES and DNS, compare to RANS

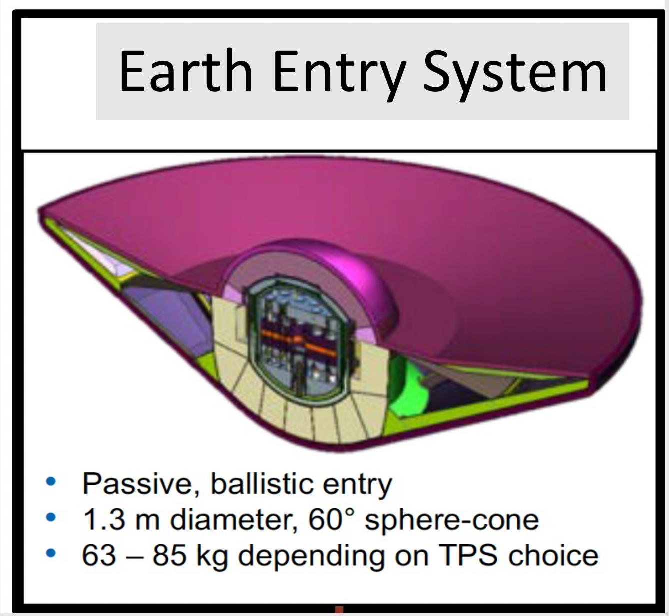
4. Improve SLA models to reduce backshell heating margin [Task 3.2]
- Generate radiative properties (scattering, absorption), evaluate influence for Dragonfly radiation environment

5. Reduce parameter variances for QMU [Task 4.2]
- Sensitivity analysis to identify dominant sources of uncertainty and utilizing targeted experiments and ab initio calculations

All Focus Areas require continuous progress in Task 2

Exemplar Project 2: Earth Entry System (Years 2.5-5)

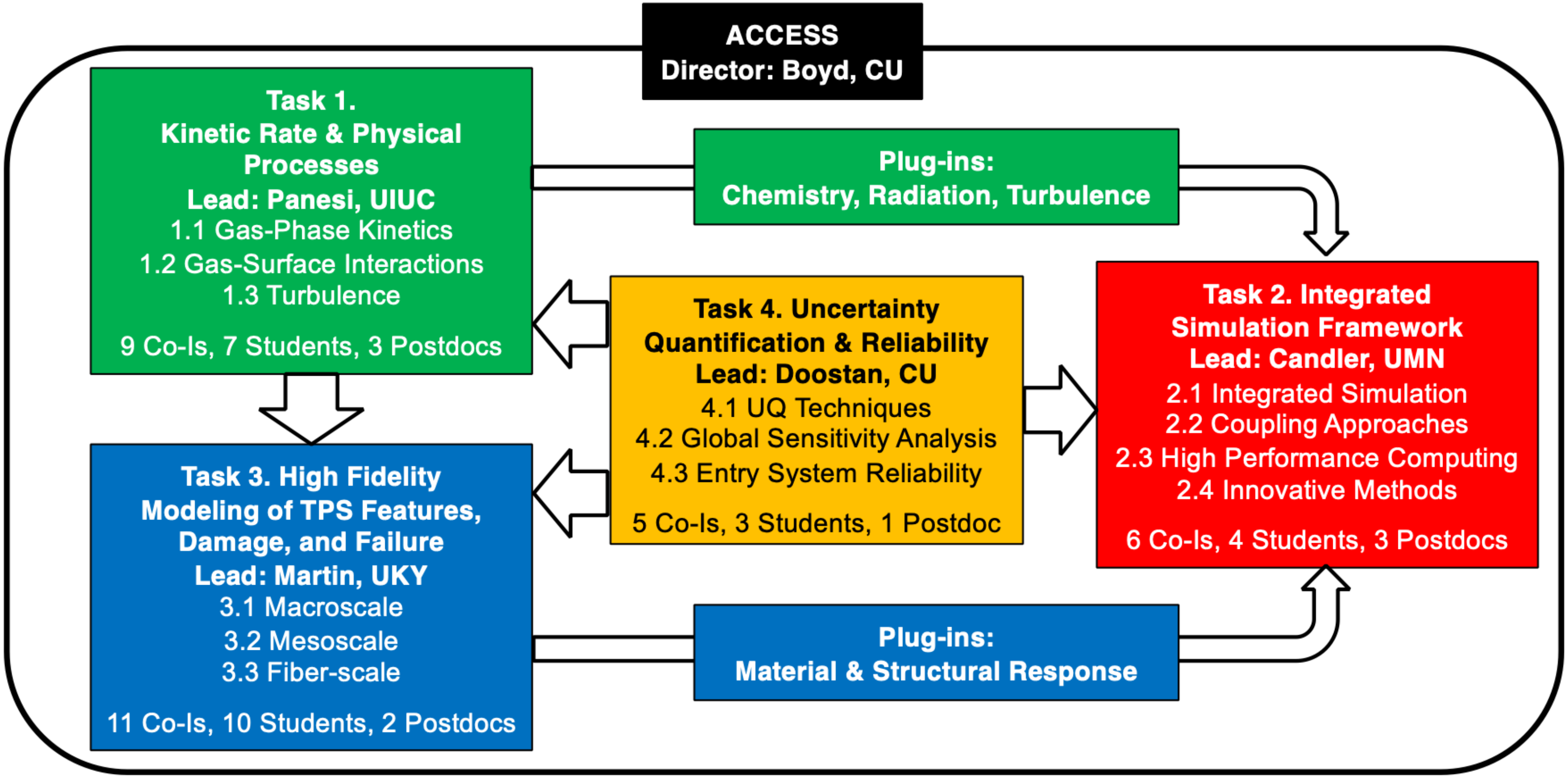
- Entry Mission: Mars Sample Return
  - Return soil samples from Mars
- Entry Environment:
  - 14 km/s, fastest ever man-made entry
- Entry System: Earth Entry System (EES)
  - Heatshield TPS = 3MDCP
  - Backshell = Paneled PICA
  - Required Reliability = 0.999999!
- Key technical considerations
  - Ionization and radiation
  - Micro-meteoroid damage
  - UQ requires 100s of ISF simulations (flow+radiation+material+structure)



Earth Entry System

- Passive, ballistic entry
- 1.3 m diameter, 60° sphere-cone
- 63 – 85 kg depending on TPS choice

Institute Structure



ACCESS
Director: Boyd, CU

Task 1.
Kinetic Rate & Physical Processes
Lead: Panesi, UIUC
1.1 Gas-Phase Kinetics
1.2 Gas-Surface Interactions
1.3 Turbulence

9 Co-Is, 7 Students, 3 Postdocs

Plug-ins:
Chemistry, Radiation, Turbulence

Task 4. Uncertainty Quantification & Reliability
Lead: Doostan, CU
4.1 UQ Techniques
4.2 Global Sensitivity Analysis
4.3 Entry System Reliability

5 Co-Is, 3 Students, 1 Postdoc

Task 2. Integrated Simulation Framework
Lead: Candler, UMN
2.1 Integrated Simulation
2.2 Coupling Approaches
2.3 High Performance Computing
2.4 Innovative Methods

6 Co-Is, 4 Students, 3 Postdocs

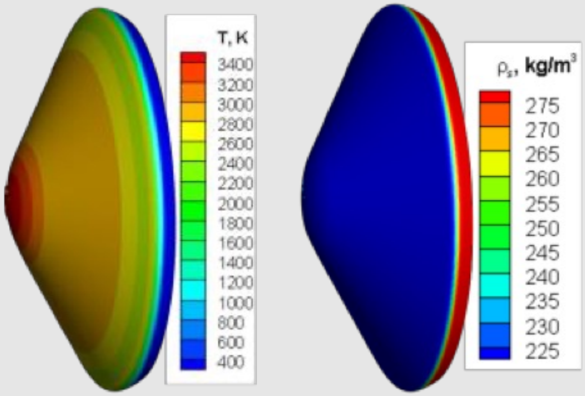
Task 3. High Fidelity Modeling of TPS Features, Damage, and Failure
Lead: Martin, UKY
3.1 Macroscale
3.2 Mesoscale
3.3 Fiber-scale

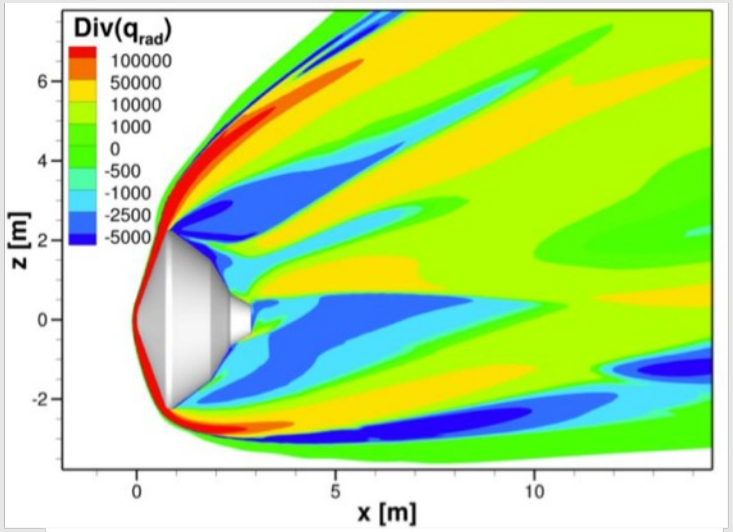
11 Co-Is, 10 Students, 2 Postdocs

Plug-ins:
Material & Structural Response

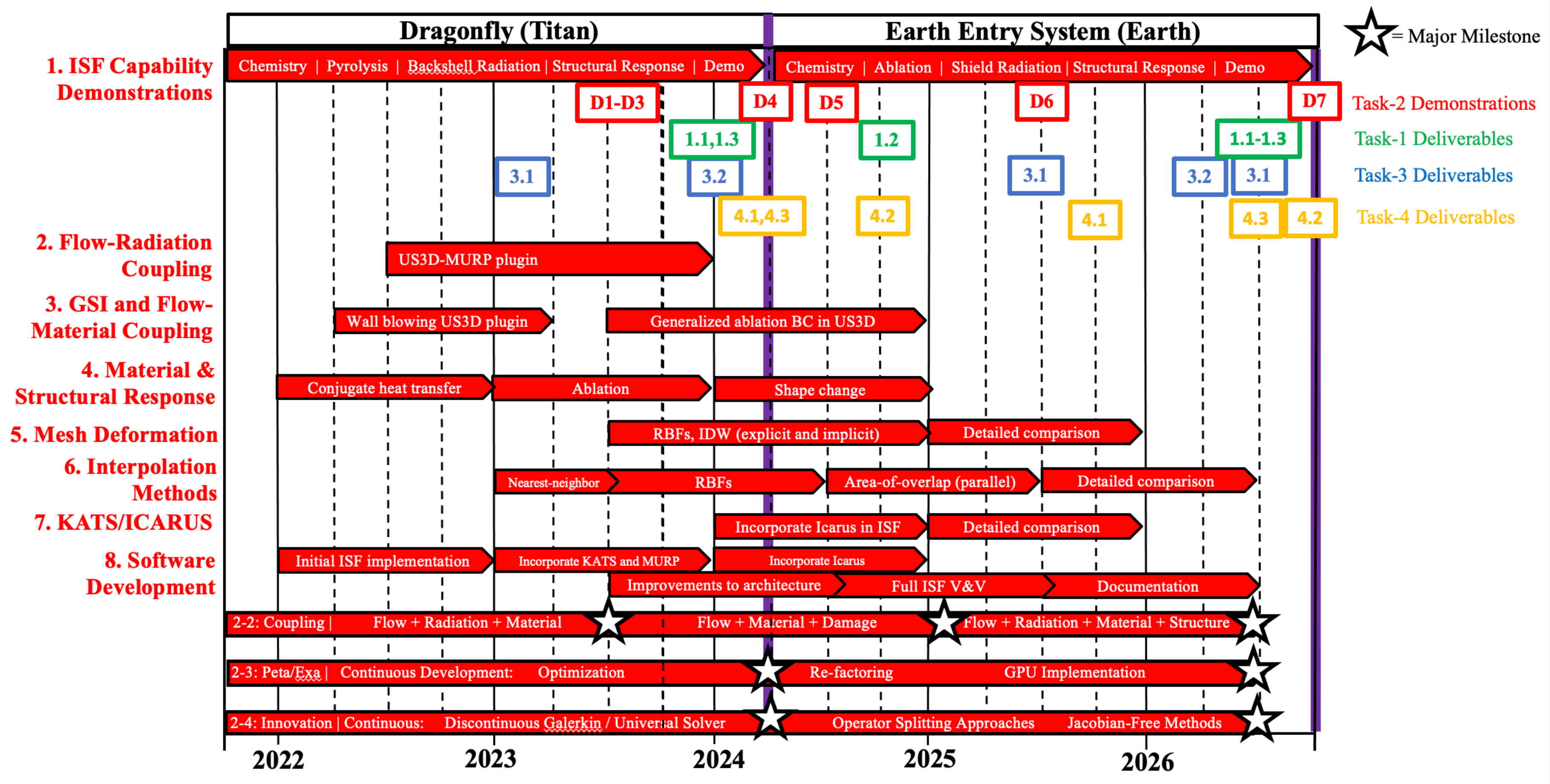
Tightly Coupled Multidisciplinary Analysis Capability (Task 2)

- **Lead:** Graham Candler, UMN
- **Objective:** Implement fully coupled flow-radiation-surface-material-structural models for entry system analysis in an Integrated Simulation Framework (ISF)
- Couple and integrate high-fidelity physics models, UQ methods, and novel scalable algorithms for emerging HPC systems
- Four sub-tasks:
  - ISF Development
  - Coupling approaches
  - Peta/exa-scale computing capabilities
  - Innovative and non-traditional methods





Roadmap for ISF Development



Dragonfly (Titan) | Earth Entry System (Earth)

☆ = Major Milestone

1. ISF Capability Demonstrations
Chemistry | Pyrolysis | Backshell Radiation | Structural Response | Demo
Chemistry | Ablation | Shield Radiation | Structural Response | Demo

D1-D3, D4, D5, D6, D7 — Task-2 Demonstrations
1.1,1.3, 1.2, 1.1-1.3 — Task-1 Deliverables
3.1, 3.2, 3.1, 3.2, 3.1 — Task-3 Deliverables
4.1,4.3, 4.2, 4.1, 4.3, 4.2 — Task-4 Deliverables

2. Flow-Radiation Coupling
US3D-MURP plugin

3. GSI and Flow-Material Coupling
Wall blowing US3D plugin
Generalized ablation BC in US3D

4. Material & Structural Response
Conjugate heat transfer
Ablation
Shape change

5. Mesh Deformation
RBFs, IDW (explicit and implicit)
Detailed comparison

6. Interpolation Methods
Nearest-neighbor
RBFs
Area-of-overlap (parallel)
Detailed comparison

7. KATS/ICARUS
Incorporate Icarus in ISF
Detailed comparison

8. Software Development
Initial ISF implementation
Incorporate KATS and MURP
Incorporate Icarus
Improvements to architecture
Full ISF V&V
Documentation

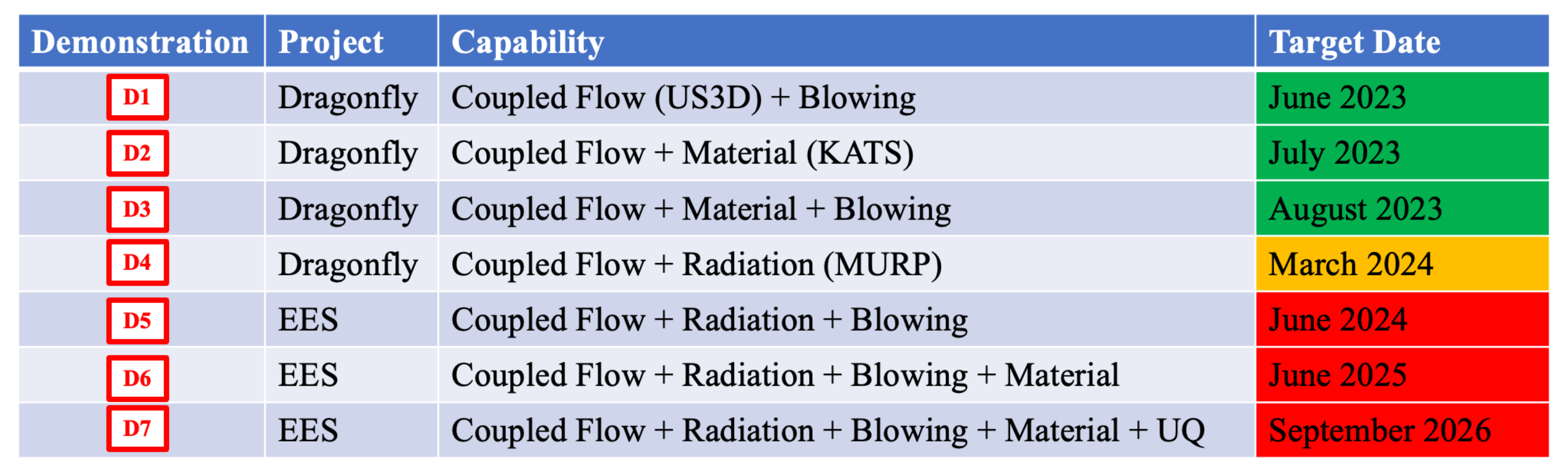
2-2: Coupling | Flow + Radiation + Material ☆ Flow + Material + Damage ☆ Flow + Radiation + Material + Structure ☆

2-3: Peta/Exa | Continuous Development: Optimization ☆ Re-factoring GPU Implementation ☆

2-4: Innovation | Continuous: Discontinuous Galerkin / Universal Solver ☆ Operator Splitting Approaches Jacobian-Free Methods ☆

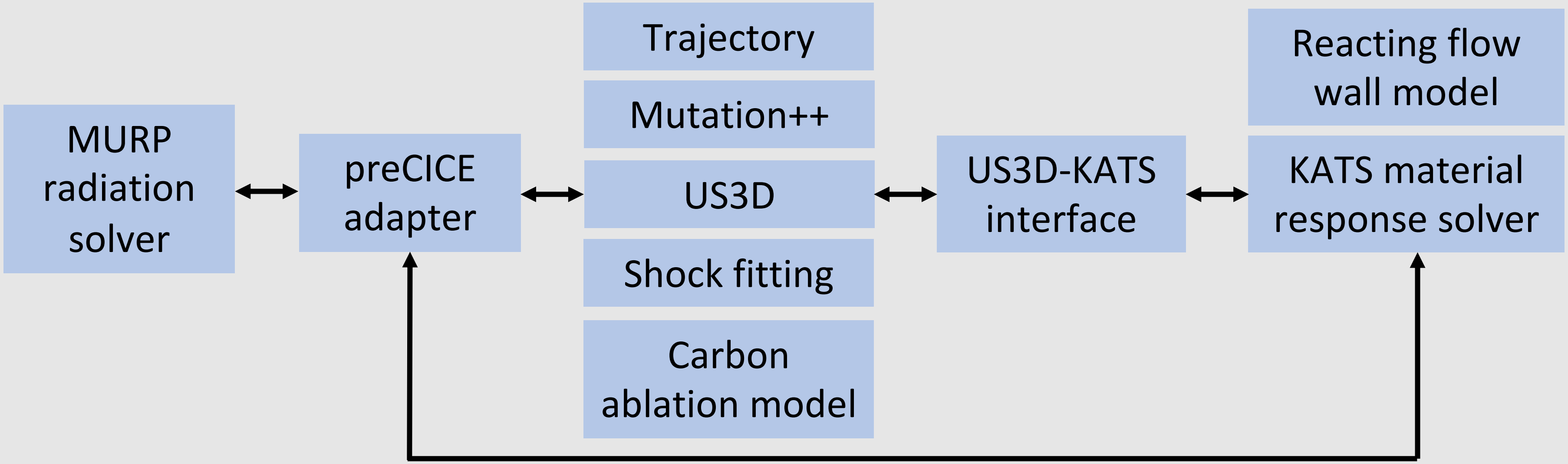
2022 2023 2024 2025 2026

Roadmap for ISF Development: Demonstrations



Demonstration	Project	Capability	Target Date
D1	Dragonfly	Coupled Flow (US3D) + Blowing	June 2023
D2	Dragonfly	Coupled Flow + Material (KATS)	July 2023
D3	Dragonfly	Coupled Flow + Material + Blowing	August 2023
D4	Dragonfly	Coupled Flow + Radiation (MURP)	March 2024
D5	EES	Coupled Flow + Radiation + Blowing	June 2024
D6	EES	Coupled Flow + Radiation + Blowing + Material	June 2025
D7	EES	Coupled Flow + Radiation + Blowing + Material + UQ	September 2026

Coupled Flow + Radiation



MURP radiation solver

preCICE adapter

Trajectory

Mutation++

US3D

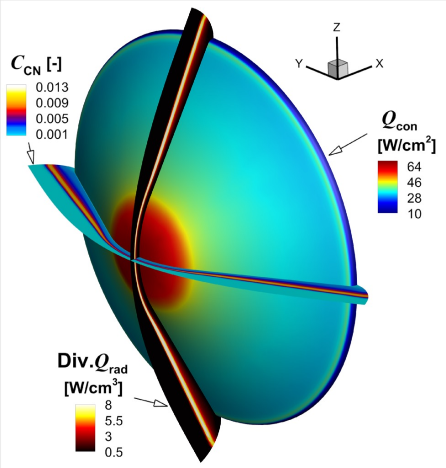
Shock fitting

Carbon ablation model

US3D-KATS interface

Reacting flow wall model

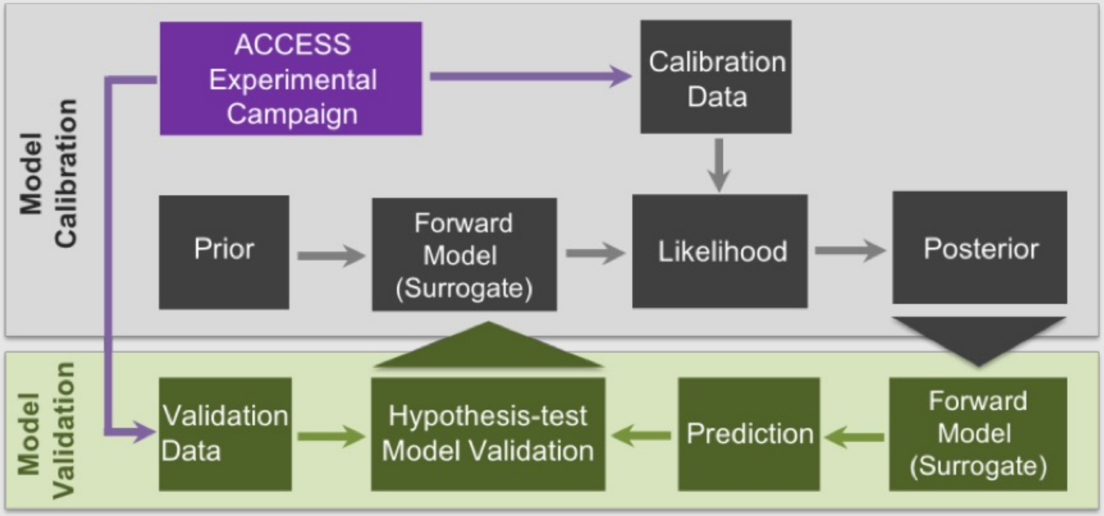
KATS material response solver



Radiative transport over Dragonfly capsule from CN Violet band (B-X) 400-430 nm

Uncertainty Quantification & Reliability (Task 4)

- **Lead:** Alireza Doostan, CU
- **Objective:** Propagation of uncertainty through model reduction approaches first at the component-level, and then at the system level
- Component-level UQ enables exploration of the uncertainty space associated with smaller sets of physics models and identify key parameters dominating the system response
- UQ of smaller sets of physics models used as a prerequisite for overall system model UQ
- Three sub-tasks:
  - UQ Development
  - Sensitivity Analysis
  - System Reliability



Model Calibration

ACCESS Experimental Campaign

Calibration Data

Prior

Forward Model (Surrogate)

Likelihood

Posterior

Model Validation

Validation Data

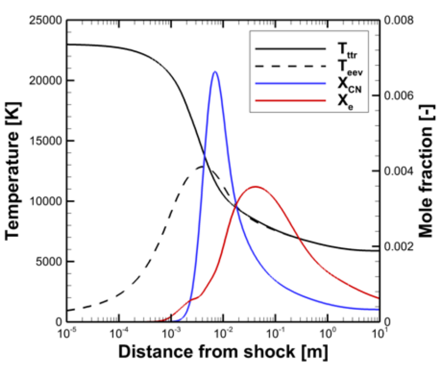
Hypothesis-test Model Validation

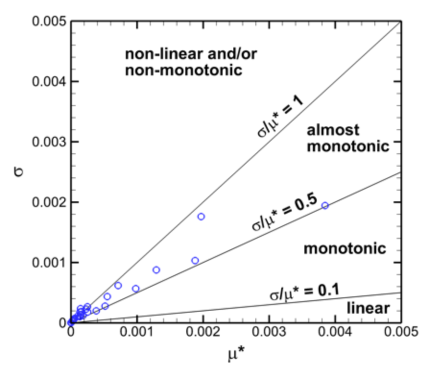
Prediction

Forward Model (Surrogate)

Sensitivity Analysis

Sensitivity Analysis: 1D shock flow simulation of Titan chemistry





$C+N_2 \Rightarrow CN+N$

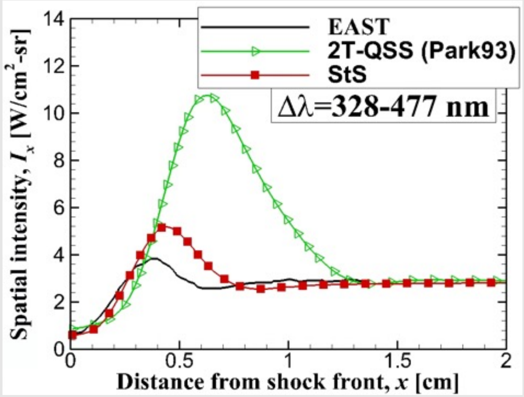
$N_2+M \Rightarrow 2N+M$

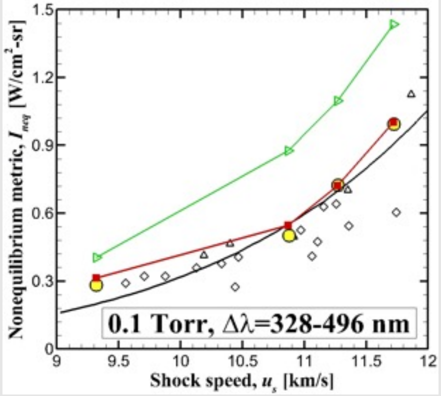
$CN+M \Rightarrow C+N+M$

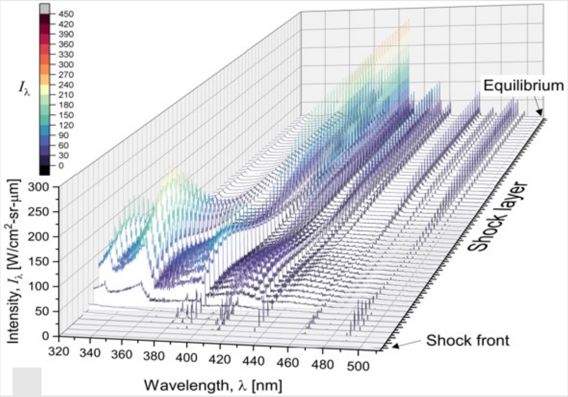
$C+e^- \Rightarrow C^++2e^-$

$N_2+e^- \Rightarrow 2N+e^-$

Towards Bayesian Calibration: Titan chemistry UQ using NASA EAST spectra

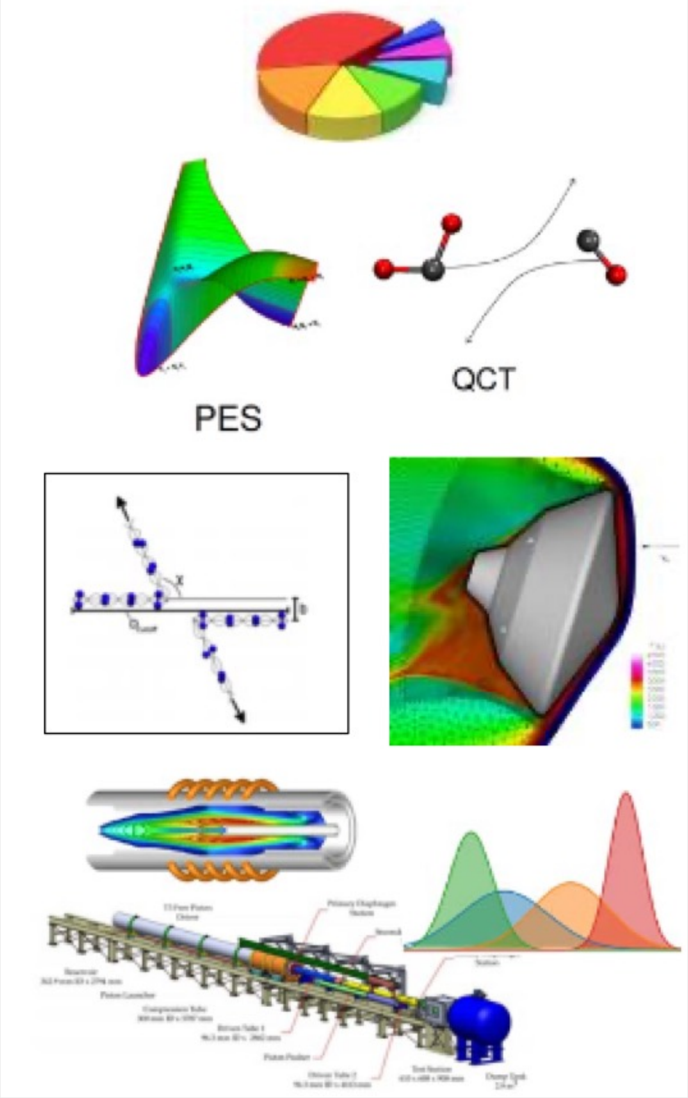






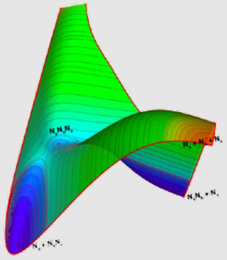
Kinetic Rate and Physical Process Modeling (Task 1)

- **Lead:** Marco Panesi, UIUC
- **Objective:** Provide accurate models of all gas-phase and gas-surface processes with quantified uncertainty
- Three sub-tasks:
  - Gas-Phase Kinetics and Radiation
  - Gas-Surface Interaction
  - Turbulence Modeling
- Models for the atmospheres of Titan, Mars, and Earth, expanded by the products of material ablation
- Research priorities guided by sensitivity analysis (Task 4)

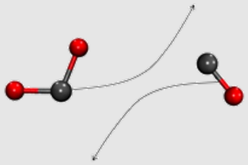


Gas Phase Chemistry and Radiation

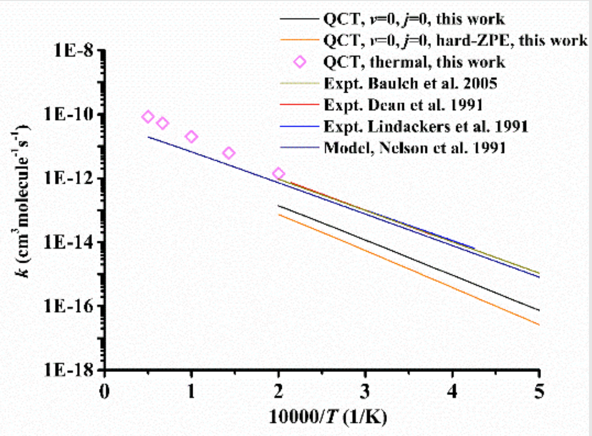
- **Dragonfly:** Construction of potential energy surfaces (PES) and use in quasi-classical trajectory (QCT) analysis for interactions in Titan atmosphere (N_2, CH_4)
  - Identified through sensitivity analysis, e.g., CN formation important for radiation
  - Rates of chemical reactions for flow analysis
- Construction of a suite of reduced order and high-fidelity flow models to test chemistry and radiation (also used for UQ in Task 4)
- Experimental data sets from several facilities
  - Inductively Coupled Plasma (UIUC)
  - Shock tubes (Oxford, IST)
  - NASA EAST facility
- Models with quantified uncertainty to be implemented in the Integrated Simulation Framework



PES



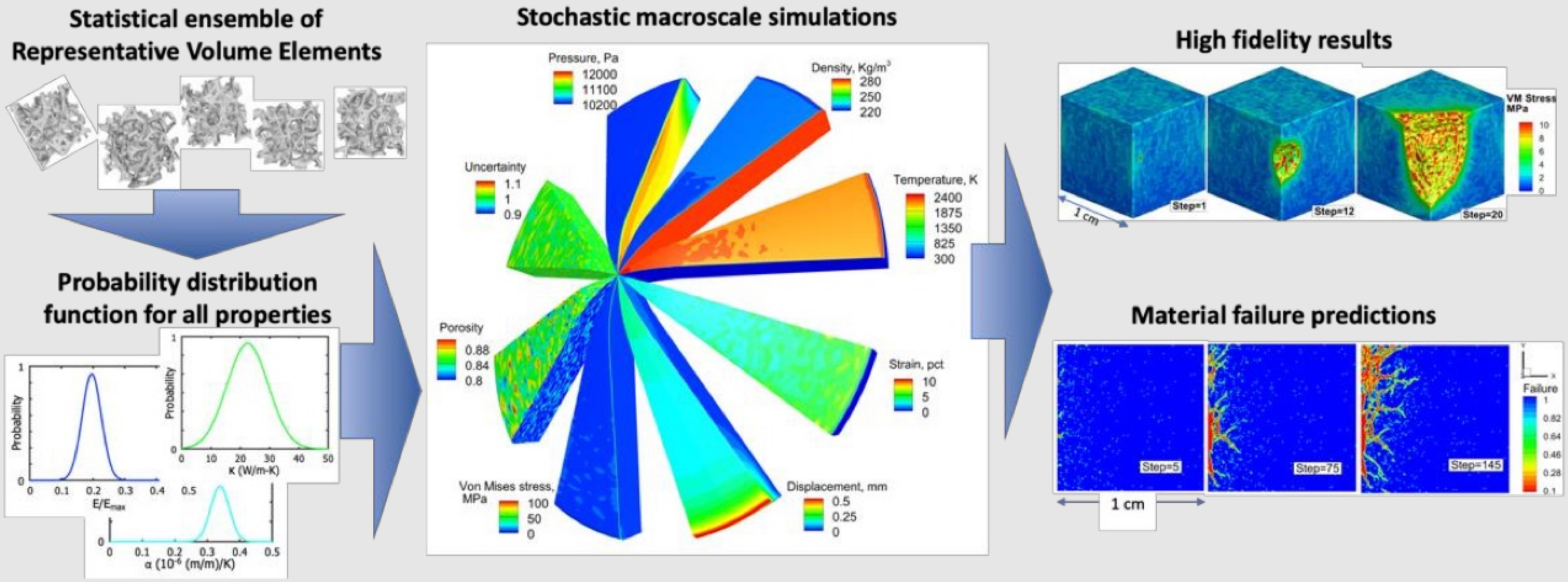
QCT



$C + N_2 \rightarrow CN + N$

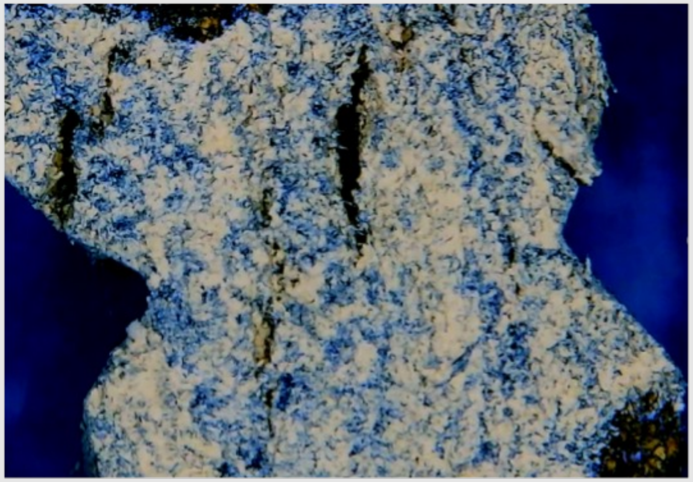
High Fidelity Modeling of TPS Features, Damage & Failure (Task 3)

- **Lead:** Alexandre Martin, UKY
- **Objective:** Provide accurate models of all material and structural response processes including features, defects, and quantified uncertainty
- Modeling and experiments at multiple scales: fiber, meso, macro
- Three sub-tasks across Macro-, Meso-, and Fiber- scales

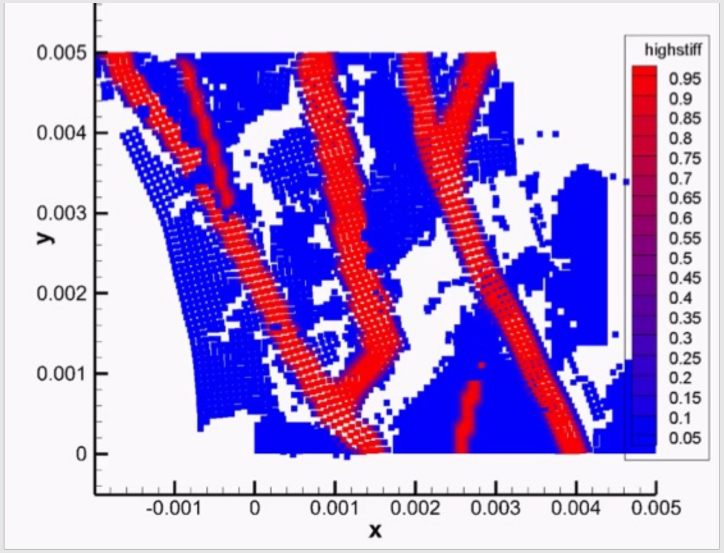


Macroscale Modeling
Material Response

Stochastic macroscale modeling of heat shields through the development of a Material Response framework (KATS)



(a) Shear Experiment



(b) Computational model of shear experiment

- Crack modeling in KATS
  - Modeling of an experiment performed by CU (D. Marshall)
  - Highlights the variability of properties based on fiber density
  - The new model captures fracturing effect seen in the experiment

Educational Activities

- Education and training opportunities
  - 27 graduate students and 10 research staff directly supported
  - Graduate Hypersonics Certificates
    - University of Colorado (23 currently enrolled, 23 awarded)
    - University of Illinois (first year)
- ACCESS Seminar Series:
  - ”Challenges in Hypersonic Entry Systems for Space Exploration”
  - Initiated in Fall 2022, nine seminars so far
  - Speakers: Government, Industry, Academia
  - Made available to all ACCESS participants and NASA
  - Strong attendance (average = 70, max = 120)

Summary

- ACCESS involves a comprehensive research team addressing the NSTRI Entry System objectives
  - Six U.S. universities, 3 international collaborators
- ACCESS approach involves
  - High fidelity modeling of all relevant flow physics, material and structural response processes, with uncertainty quantified using detailed comparisons of analysis and experiments
  - Implementation of all models in the Integrated Simulation Framework executed on exa/peta-scale hardware to enable reliability estimation
  - Use of two exemplar projects to successively advance capabilities
- Successful completion of the ISF will enable the comprehensive and affordable analysis of Entry Systems with quantified uncertainty and reliability estimates for adoption by NASA and industry

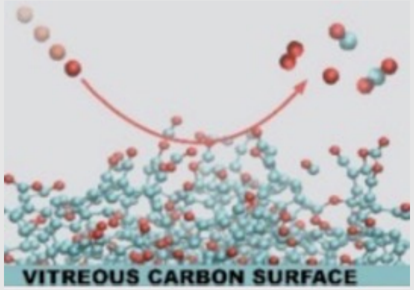
Backup

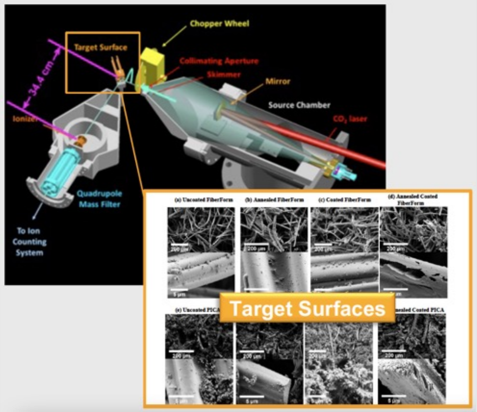
NSTRI
FY20 Entry System Topic

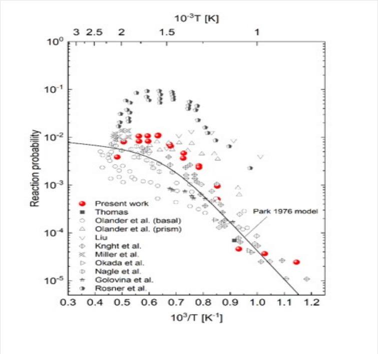
- **NASA is facing new challenges in certifying Entry Systems of some future exploration missions**
- **Example: Mars Sample Return**
  - Send rover to surface of Mars and collect soil samples
  - Return samples to Earth for study
  - Entry system for Earth required to have reliability of 0.999999
    - Planetary contamination concern if vehicle breaks up
- **NASA and contractors have no way today to certify to that level**
- **NSTRI proposal requirements**
  - Advance the state-of-the-art in modeling of all flow, materials, and structures phenomena in the context of uncertainty quantification (UQ)
  - Integrate all models including UQ into a single computational simulation capability for evaluation of entry system reliability

Gas-Surface Interaction

- **Dragonfly:** Construction of a model for the interaction of the Titan atmosphere (N_2, CH_4) with heatshield material (PICA: a pyrolyzing light-weight ablator)
  - No ablation expected in oxygen-free atmosphere
  - Primary focus is N_2 interaction with carbon surface
  - Ab initio computational simulations
- Pyrolysis chemistry
  - Interaction of pyrolysis products (CO, CO_2, H_2O, etc.) with N_2, CH_4
  - Pyrolysis chemistry internal to PICA
- Experimental data sets from several facilities
  - Inductively Coupled Plasma (UIUC)
  - Flow reactor (CU)
  - Molecular beams (CU)
- Models with quantified uncertainty to be implemented in the Integrated Simulation Framework



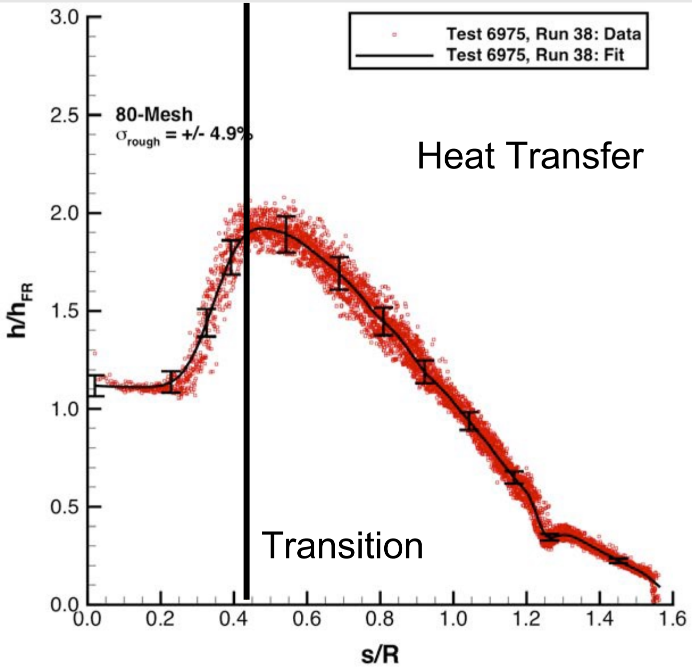


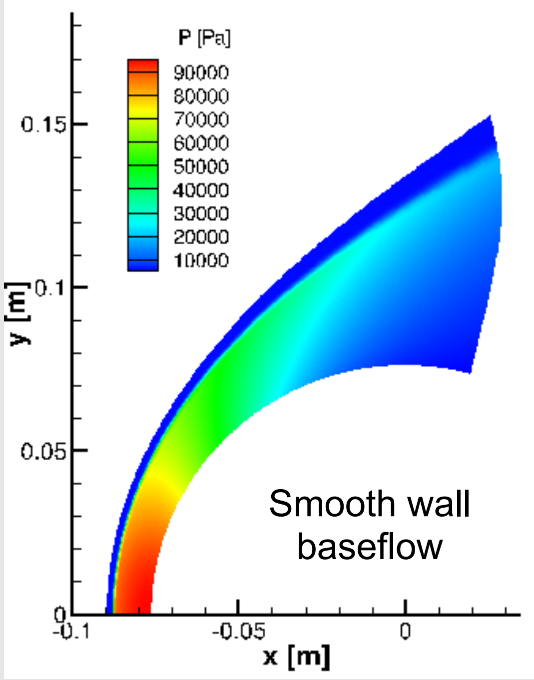


Turbulence and Transition

- Hypersonic turbulent boundary layers can have heating rates that are factors of 3-6 higher than laminar flows, so transition prediction is particularly important
  - Complicated by chemistry of different atmospheres, blowing of ablation products, and surface roughness

Analysis of experiments from NASA Langley Mach 6 Tunnel of hemisphere with sand grain roughness (Hollis, 2017)

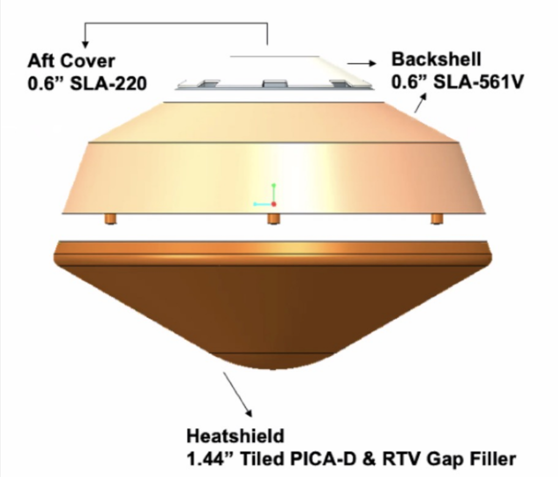




High Fidelity Modeling of TPS: Dragonfly Approach

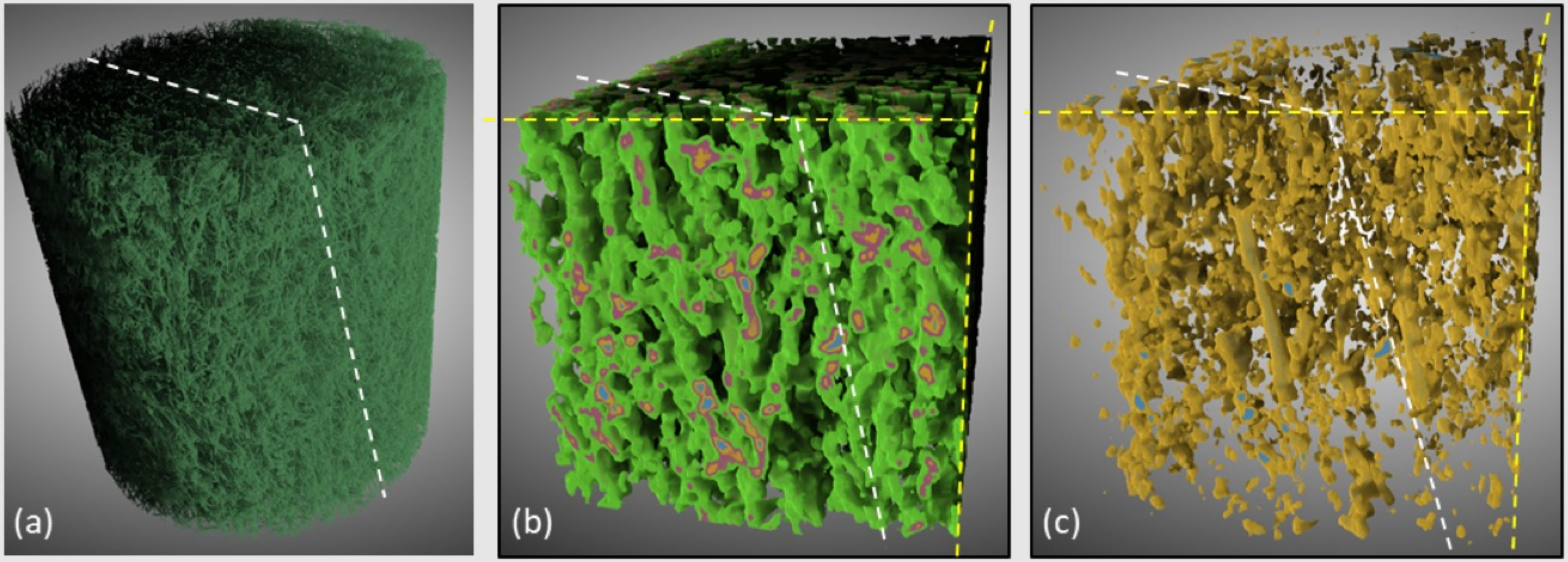
- Material response modeling
  - Non-oxidizing environment; first N_2, then N_2-CH_4
  - Focus on FiberForm (before PICA)
- Experimental characterization of RTV gap filler for input to modeling
  - Micro-CT, TGA
- Experiments focus on non-oxidizing environment:
  - Flow tube
  - Effective conductivity under load
  - Nitridation of microstructure
- Pyrolysis gas of PICA
  - Chemistry
  - Transport properties
  - Volumetric oxidation

- Backshell – SLA-561 and SLA-220
  - Very different from PICA
  - No surface recession expected (relatively mild heat flux)
  - 90% of heating from radiation
  - Data obtained on micro-structure, conductivity, radiative properties
  - Objective is to improve upon current models



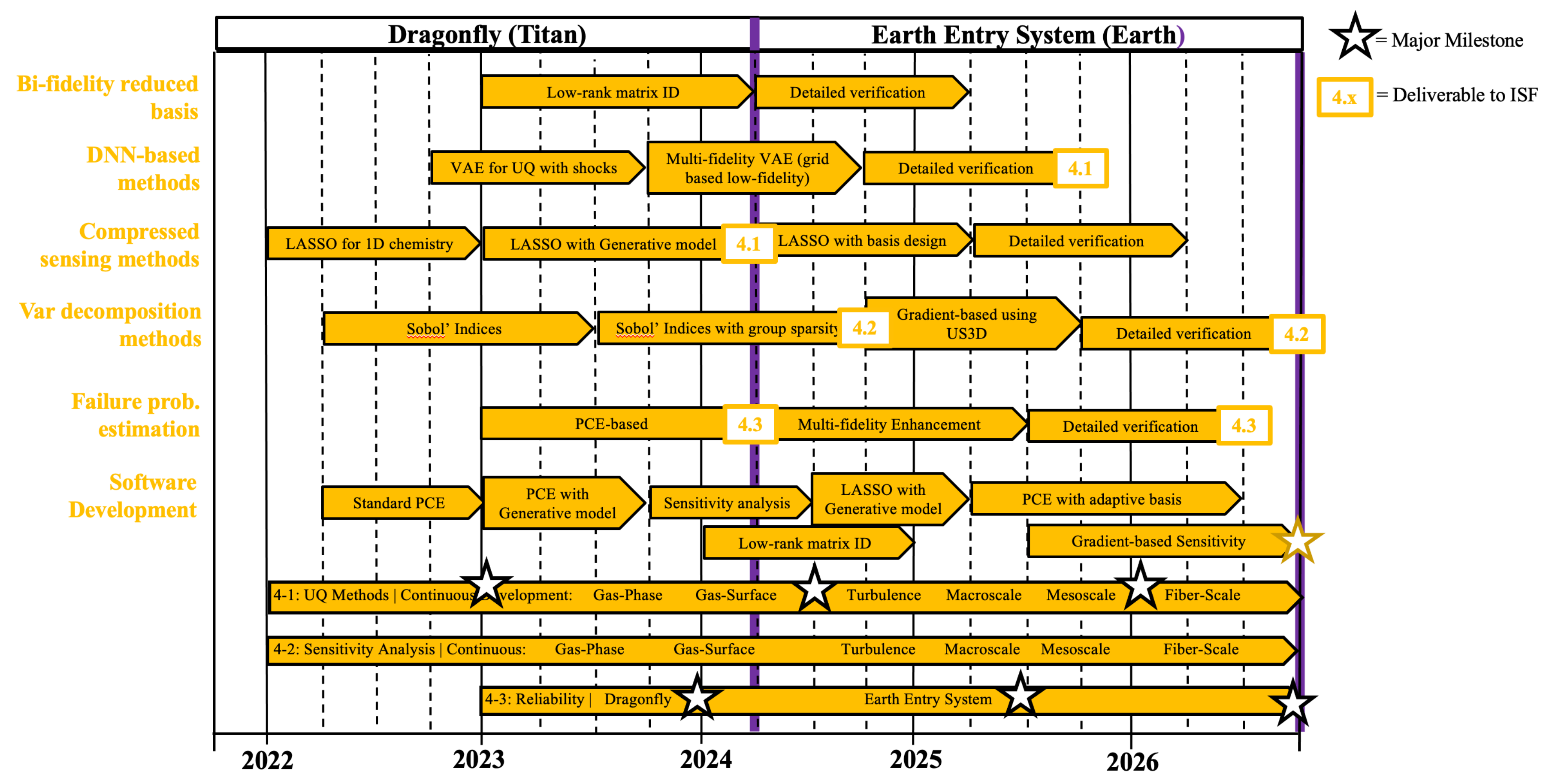
Mesoscale modeling
Structural Properties (experiment)

Characterize material structures and constitutive properties to inform and validate mesoscale models of ablation and spalling in environments relevant to DragonFly



3-D maps of local fiber packing density (volume fraction of fibers) within a 2x2x2mm cube in the interior of the cylindrical specimen

Roadmap for UQ & Reliability (Task 4)



Dragonfly (Titan) | **Earth Entry System (Earth)**

☆ = Major Milestone

4.x = Deliverable to ISF

Bi-fidelity reduced basis
- Low-rank matrix ID
- Detailed verification

DNN-based methods
- VAE for UQ with shocks
- Multi-fidelity VAE (grid based low-fidelity)
- Detailed verification 4.1

Compressed sensing methods
- LASSO for 1D chemistry
- LASSO with Generative model 4.1
- LASSO with basis design
- Detailed verification

Var decomposition methods
- Sobol' Indices
- Sobol' Indices with group sparsity 4.2
- Gradient-based using US3D
- Detailed verification 4.2

Failure prob. estimation
- PCE-based 4.3
- Multi-fidelity Enhancement
- Detailed verification 4.3

Software Development
- Standard PCE
- PCE with Generative model
- Sensitivity analysis
- LASSO with Generative model
- PCE with adaptive basis
- Low-rank matrix ID
- Gradient-based Sensitivity ☆

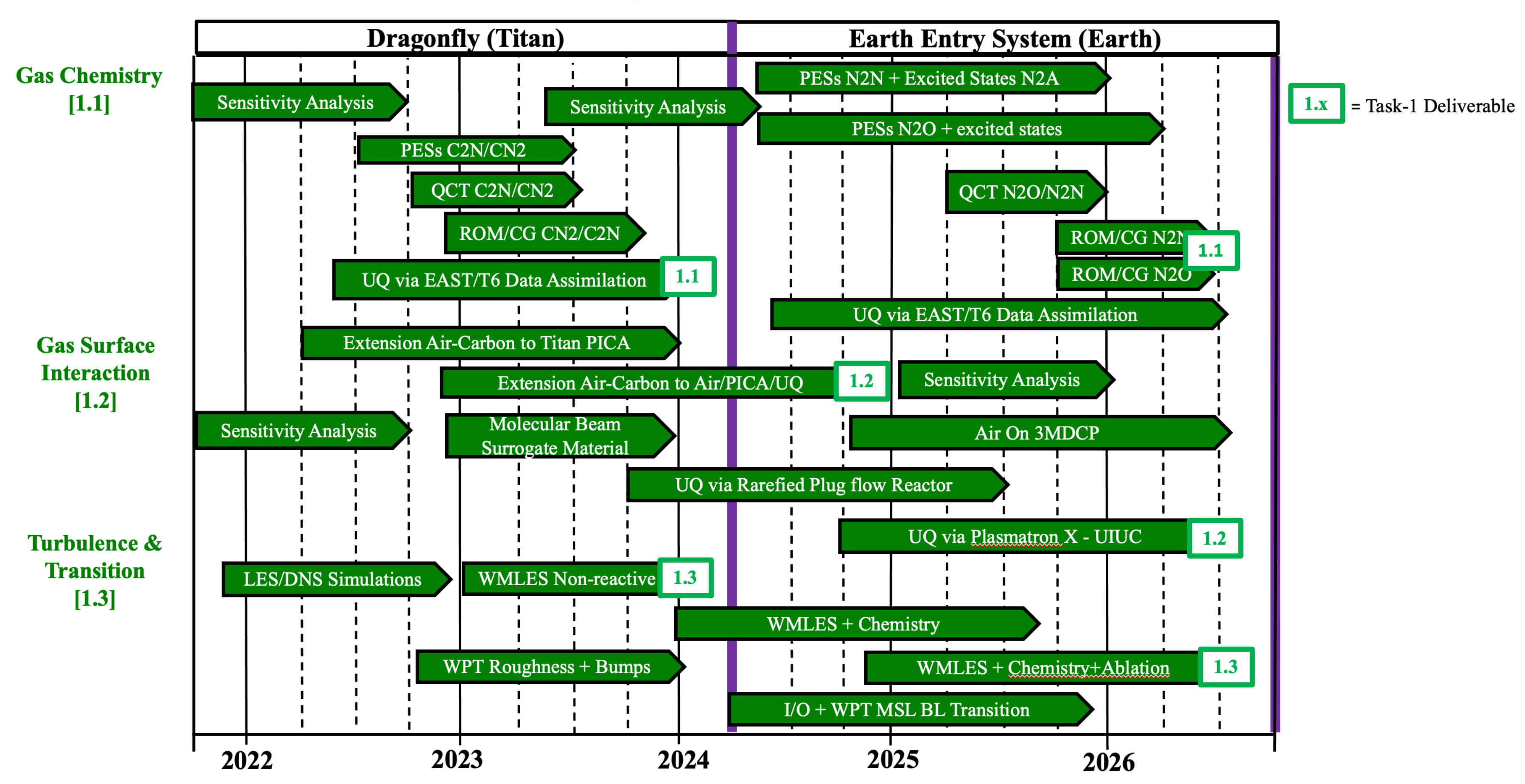
4-1: UQ Methods | Continuous Development: ☆ Gas-Phase Gas-Surface ☆ Turbulence Macroscale Mesoscale ☆ Fiber-Scale

4-2: Sensitivity Analysis | Continuous: Gas-Phase Gas-Surface Turbulence Macroscale Mesoscale Fiber-Scale

4-3: Reliability | Dragonfly ☆ Earth Entry System ☆ ☆

2022 2023 2024 2025 2026

Roadmap for Flow Physics (Task 1)



Dragonfly (Titan)

Earth Entry System (Earth)

1.x = Task-1 Deliverable

Gas Chemistry [1.1]

Sensitivity Analysis

Sensitivity Analysis

PESs N2N + Excited States N2A

PESs N2O + excited states

PESs C2N/CN2

QCT C2N/CN2

QCT N2O/N2N

ROM/CG CN2/C2N

ROM/CG N2N

ROM/CG N2O

1.1

UQ via EAST/T6 Data Assimilation 1.1

UQ via EAST/T6 Data Assimilation

Gas Surface Interaction [1.2]

Extension Air-Carbon to Titan PICA

Extension Air-Carbon to Air/PICA/UQ 1.2

Sensitivity Analysis

Sensitivity Analysis

Molecular Beam Surrogate Material

Air On 3MDCP

UQ via Rarefied Plug flow Reactor

UQ via Plasmatron X - UIUC 1.2

Turbulence & Transition [1.3]

LES/DNS Simulations

WMLES Non-reactive 1.3

WMLES + Chemistry

WPT Roughness + Bumps

WMLES + Chemistry+Ablation 1.3

I/O + WPT MSL BL Transition

2022

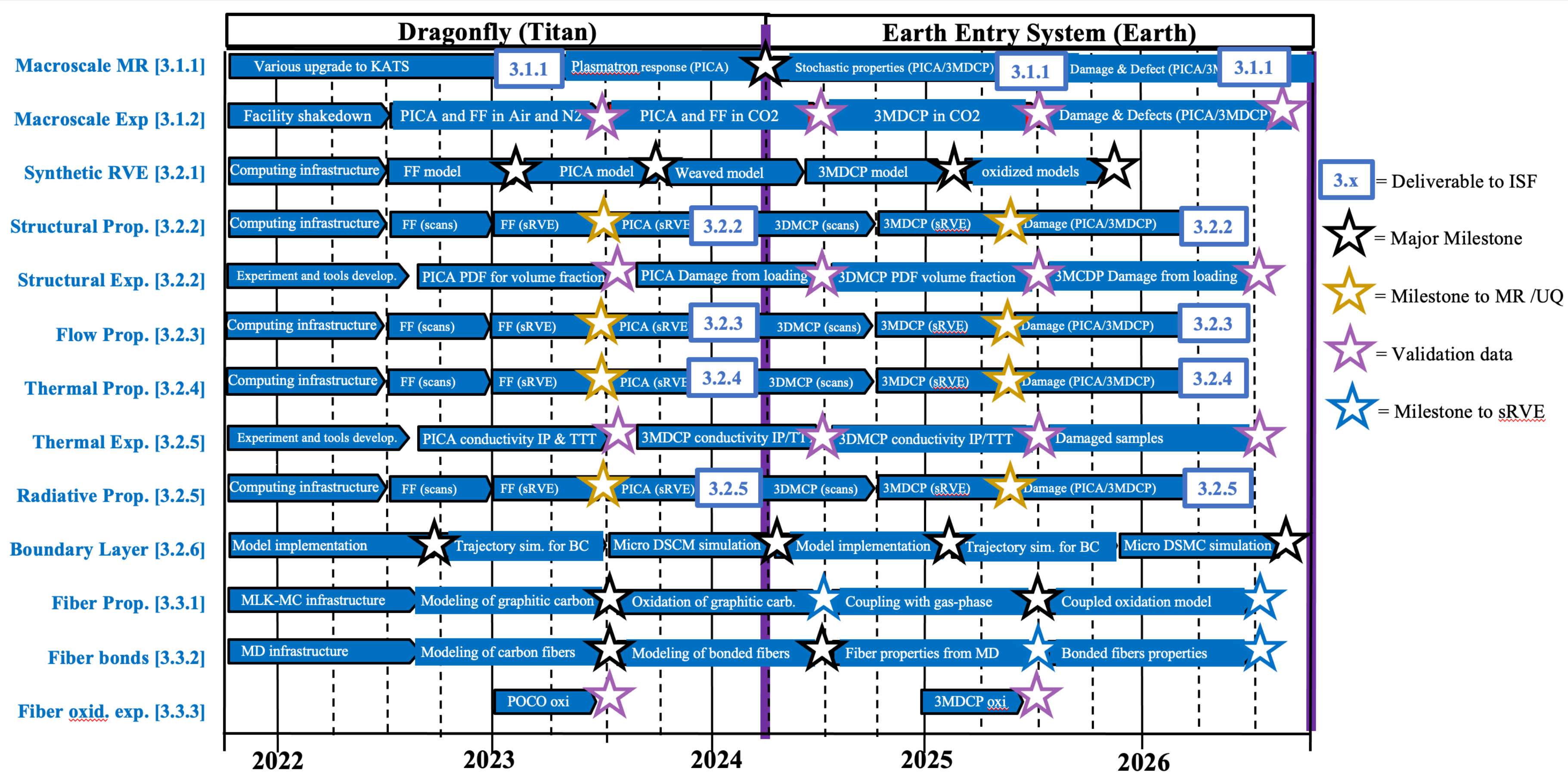
2023

2024

2025

2026

Roadmap for Materials and Structures (Task 3)



Dragonfly (Titan)

Earth Entry System (Earth)

Macroscale MR [3.1.1]: Various upgrade to KATS; 3.1.1; Plasmatron response (PICA); Stochastic properties (PICA/3MDCP); 3.1.1; Damage & Defect (PICA/3M; 3.1.1

Macroscale Exp [3.1.2]: Facility shakedown; PICA and FF in Air and N2; PICA and FF in CO2; 3MDCP in CO2; Damage & Defects (PICA/3MDCP)

Synthetic RVE [3.2.1]: Computing infrastructure; FF model; PICA model; Weaved model; 3MDCP model; oxidized models

Structural Prop. [3.2.2]: Computing infrastructure; FF (scans); FF (sRVE); PICA (sRVE; 3.2.2; 3DMCP (scans); 3MDCP (sRVE); Damage (PICA/3MDCP); 3.2.2

Structural Exp. [3.2.2]: Experiment and tools develop.; PICA PDF for volume fraction; PICA Damage from loading; 3DMCP PDF volume fraction; 3MCDP Damage from loading

Flow Prop. [3.2.3]: Computing infrastructure; FF (scans); FF (sRVE); PICA (sRVE; 3.2.3; 3DMCP (scans); 3MDCP (sRVE); Damage (PICA/3MDCP); 3.2.3

Thermal Prop. [3.2.4]: Computing infrastructure; FF (scans); FF (sRVE); PICA (sRVE; 3.2.4; 3DMCP (scans); 3MDCP (sRVE); Damage (PICA/3MDCP); 3.2.4

Thermal Exp. [3.2.5]: Experiment and tools develop.; PICA conductivity IP & TTT; 3MDCP conductivity IP/TT; 3DMCP conductivity IP/TTT; Damaged samples

Radiative Prop. [3.2.5]: Computing infrastructure; FF (scans); FF (sRVE); PICA (sRVE); 3.2.5; 3DMCP (scans); 3MDCP (sRVE); Damage (PICA/3MDCP); 3.2.5

Boundary Layer [3.2.6]: Model implementation; Trajectory sim. for BC; Micro DSCM simulation; Model implementation; Trajectory sim. for BC; Micro DSMC simulation

Fiber Prop. [3.3.1]: MLK-MC infrastructure; Modeling of graphitic carbon; Oxidation of graphitic carb.; Coupling with gas-phase; Coupled oxidation model

Fiber bonds [3.3.2]: MD infrastructure; Modeling of carbon fibers; Modeling of bonded fibers; Fiber properties from MD; Bonded fibers properties

Fiber oxid. exp. [3.3.3]: POCO oxi; 3MDCP oxi

3.x = Deliverable to ISF
☆ = Major Milestone
☆ = Milestone to MR /UQ
☆ = Validation data
☆ = Milestone to sRVE