Current Investments in the NASA Entry Systems Modeling Project

Michael Wright, PM
Michael Barnhardt, PI
Monica Hughes, DPM

TECHNOLOGY DRIVES EXPLORATION
The Overarching Goal
FY 2017 GCD PORTFOLIO (TRL 3-6)*

*Not a complete list of every activity in GCD

**Space Observatory Systems**
- Advanced 1.65 micron seed laser for Lidar remote sensing of methane (TP)
- Astrophysics Focused Telescope Assets Coronagraph
- Mars Environmental Dynamics Analyzer (MEDA)
- Nanosats for Advanced Gravity Mapping and Crosslink Occultation (TP)

**Autonomy & Robotic Systems**
- Astrobee
- Autonomous Systems (AS)
- IBM Watson Collaboration
- Mixed Reality Crew
- National Robotics Initiative
- Pop-Up Flat Folding Explorer Robotics (PUFFER)
- Rover Technologies
- Space Robotics Challenge (SRC)

**Entry, Descent & Landing Systems**
- ADEPT
- Arc Jet Exposure of Ablative and Non-Oxide CMC TPS (ACO)
- Conformal Ablative TPS
- Cooperative Blending of Auto. Landing Tech. (COBALT)
- 3D Woven TPS Arc Jet Testing (ACO)
- Entry Systems Modeling (ESM)
- Heat shield for Extreme Entry Environment Technology (HEEET)
- HIAD-2
- Entry, Descent & Landing Architecture
- MEDLI-2
- Propulsive Descent Technologies (PDT)

**HB Comm, Navigation & Avionics**
- Affordable Vehicle Avionics (AVA)
- High Performance Spaceflight Computing (HPSC)
- Station Explorer for X-Ray Timing & Navigation Tech (SEXTANT)

**Lightweight Structures & Manufacturing**
- Additive Construction w/ Mobile Emplacement (ACME)
- Additive Manufacturing for Turbomachinery
- Advanced Near Net Shape Technology (ANNST)
- Bulk Metallic Glass Gears (BMGG)
- Composite Overwrap Pressure Vessel (COPV)
- Composites Technology for Exploration (CTE)
- Deployable Composite Booms (DCB)
- Low Cost Upper Stage (LCUS)
- Nanowire Insulation

**Space Power & Propulsion**
- Extreme Environment Solar Power (EESP)
- Flight Qual of Busek’s 5N Green Monopropellant Thruster (ACO)
- Green Propellant Thruster Tech Qual (ACO)
- High Capacity Cryocooler (2020 Cooler)
- Iodine Hall Thruster (IHT)
- Nuclear Thermal Propulsion (NTP)
- Risk-Reduction Testing for the DESLA Upper Stage Engine (ACO)
- Kilopower
- MON-25/MMH Bipropellant In Space Engine (ISE-100)

**Advanced Life Support & ISRU**
- High Performance EVA Gloves (HPEG)
- In-Situ Resource Utilization (IRSU)
- SpaceCraft Oxygen Recovery (SCOR)
- Thick Galactic Cosmic Rays Shielding
### EDL Quantifiable Capabilities

<table>
<thead>
<tr>
<th><strong>(1) High Mass to Mars Surface (HMMS)</strong></th>
<th><strong>(2) Planetary Probes &amp; Earth Return Vehicles (PP/ERV)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Challenge:</strong> Land 20 t payload on Mars surface in support of the human Evolvable Mars Campaign</td>
<td><strong>Challenge:</strong> Convective heating at &gt; 7000 W/cm², significant radiative heating, 9+ atm pressure. High reliability for planetary protection (&lt;10⁻⁶ chance of failure).</td>
</tr>
<tr>
<td><strong>Description:</strong> Includes hypersonic, supersonic, and subsonic deceleration technologies to enable large-scale Mars missions. Requires a long-term development, including large-scale ground and flight tests at Earth. Largely NASA effort, some industry.</td>
<td><strong>Description:</strong> Includes the Thermal Protection System (TPS) and integrated entry vehicle system technologies for Venus, Saturn, Titan, Uranus, Neptune science missions, as well as high-speed Earth return of samples from comets, asteroids, moons, and Mars.</td>
</tr>
<tr>
<td><strong>Contents/Options:</strong> Hypersonic: HIAD, ADEPT, Mid-L/D, Capsule or Mixed Fleet Supersonic: Retropropulsion (SRP) Subsonic: Propulsion with PLHA (see below)</td>
<td><strong>Contents/Options:</strong> TPS materials; low-mass integrated vehicle designs for high reliability; analysis; test facilities capabilities; aerocapture</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>(3) Precision Landing &amp; Hazard Avoidance (PLHA)</strong></th>
<th><strong>(4) EDL Data Return &amp; Model Improvement (DRMI)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Challenge:</strong> Robotic Mars: 10-100 m landing footprint, challenging terrains like Europa; Human Mars: land within 50 m of target</td>
<td><strong>Challenge:</strong> Reduce by 50% uncertainties in convective and radiative heating, backshell heating, and dynamic stability coefficients; improve model correlation with validation datasets by factors of two or more; instrument every EDL vehicle (&lt;$5M).</td>
</tr>
<tr>
<td><strong>Description:</strong> Includes sensors and algorithms to enable robotic and human missions to land safely in hazardous terrain, in locations of scientific interest or near pre-deployed assets. Largely NASA effort, some academia and industry.</td>
<td><strong>Description:</strong> Aggressively improve the speed and accuracy of critical models and tools NASA uses to design EDL vehicles, resulting in reduced mission cost and risk through better understanding of the system and environments.</td>
</tr>
<tr>
<td><strong>Contents/Options:</strong> Low-SWaP optical, LIDAR, and other sensors; guidance, navigation and control algorithms; high-performance, real-time computational hardware and software</td>
<td><strong>Contents/Options:</strong> Partnerships with academia and OGAs are heavily leveraged to explore multiple techniques and obtain validation data.</td>
</tr>
</tbody>
</table>
NASA Has Models in all Major Disciplines… Are We There Yet?

- Models, particularly in aero sciences and material response, have largely undefined uncertainty levels for many problems (limited validation)
  - Without well defined uncertainty levels, it is difficult to assess system risk and to trade risk with other subsystems
    - Result is typically (but not automatically) overdesign

- Missions get more ambitious with time
  - Tighter mass and performance requirements
  - More challenging EDL conditions require that models evolve

- Even reflights benefit from improvement
  - Reflights are never truly reflights; changing system performance requires new analysis, introduces new constraints
  - ‘New physics’ still rears its head in the discipline

- Some of the most challenging problems have the “worst” models
  - Parachute dynamics, separation dynamics, TPS failure modes, backshell radiation
  - These are all focus areas for this proposal…

“Since atmospheric and surface conditions of planetary surfaces are so varied [...] it is virtually impossible to test all aspects of EDL as they would be performed when landing. Consequently, we have to rely on M&S to give us confidence we can choose the right technologies and successfully perform EDL wherever we land. It is critical to develop validated physics-based models for the flight systems and sub-systems – for the TPS, parachutes and proximity operations. We need to fully understand off-nominal scenarios and be able to design fault tolerant systems that will work autonomously.”

-- Pat Beauchamp, Chief Technologist, JPL Engineering & Science Directorate

Focused investment in EDL M&S, guided by mission challenges, ensures that NASA is ready to execute the challenging missions of tomorrow
The Entry Systems Modeling Project

- Formed in 2013 within Space Technology Mission Directorate’s Game Changing Development Program
- Grew out of prior pursuits funded by Fundamental Aeronautics Hypersonics Project and Entry, Descent, and Landing Technology Development Project

The primary objective of the ESM Project is to develop enabling technologies and tools for hypersonic entry system design and development.

- **Aerosciences**
  - Flight mechanics, CFD, vehicle dynamics, parachute dynamics, turbulence

- **Shock Layer Radiation**
  - Chemical kinetics, spectral properties

- **Model Validation**
  - Turbulent heating, transition, shock interaction, etc.

- **Thermal Protection Materials**
  - Fibrous ablators, flexibles, woven, micro-to-macro scale modeling

- **EDL Systems**
  - Early-phase design, concepts, sub-system proof-of-concept
Next-Generation CFD Software

• **US3D (partnership with University of Minnesota)**
  - Unstructured, High-accuracy, Adaptive Mesh Refinement, Fluid-Structure Interaction

• **Hypersonic FUN3D**
  - Added thermochemical non-equilibrium
  - Walsh Functions for resolving

• **Multiphysics Algorithm with Particles (MAP)**
  - New DSMC code provides independent path for innovation
Entry Vehicle Dynamics

• **Magnetic Suspension Wind Tunnel**
  - Refurbished subsonic tunnel, magnetic balance, and electronic positioning system at Langley
  - New supersonic test section for Glenn 225 cm² tunnel

• **Free-flight CFD**
  - Desktop ballistic range
  - Provide detailed predictions of vehicle dynamics and driving physics
  - Application on several NASA projects

![Simulated flight of ballistic range model](image1)

![Predicted vehicle dynamics vs Experiment](image2)
Parachute Fluid-Structure Interaction

- **eddy CFD solver**
  - Fully-coupled fluid-structure model
  - Intended for high risk applications
- **Space Technology Research Grants**
  - Focused on inflation problem: Self-contact, canopy and line stress
  - Stochastic deployment models

Micro-CT imaging of parachute fabric
Shock Layer Radiation

- **Electric Arc Shock Tube (EAST)**
  - 4” aluminum (High Velocity) and 24” steel (Low Density)
  - Uncertainty reduction for air from 200% to 17%
  - Informed detailed radiation margin policy for Orion
  - Next Up: Mars, Venus, Outer Planets…
- **Theoretical Chemistry**
- **NEQAIR and HARA**
  - Workhorse radiation tools for design applications
  - Orion, Mars 2020, InSight, OSIRIS-REx, industry
Thermal Protection Materials

- Conformal / Flexible TPS
  - Established two 75 W/cm² layups, tested successfully up to 100 W/cm²
- Convective Heating Improvement for Emergency Fire Shelters (CHIEFS)
  - Applying entry technology to protect firefighters

Left: Commercial manufacture of CHIEFS fire shelter

Right: Interior images of shelter tests show dramatic improvement over currently deployed USFS shelter
• **Micro-CT and Material Characterization**
  - Detailed 3-D imaging
  - Porous Media Analysis (PuMA)

• **Engineering and Design**
  - Pyrolysis and Ablation Toolbox in OpenFOAM (PATO)
  - Icarus

**Micro-CT imaging of materials enables highly accurate characterization of material properties**

**DSMC (with SPARTA) simulation of FiberForm**

**Improved micro-scale model for carbon/phenolic material (from article submitted to *Carbon*)**
Two (Opposite) Directions of Research

• **We need to better understand our materials at the microstructural level**
  - TPS materials are not homogeneous substances. Understanding and modeling their constituent properties and morphology enables a much deeper understanding of performance
  - We need more physics in the simulations

• **We need to model TPS as a system**
  - Entire heatshield simulations enable model-based understanding of singularities and thermostructural effects.
  - Models informed by microstructural data to include maximum fidelity at an engineering level of design
We want to go from here:

TPS Material

To here:

To enable a microstructural understanding of the materials

Credit: Ferguson (STC/ARC)
...Enables Deeper Understanding...

- Better understanding of microstructure directly feeds higher fidelity macroscale models

Tomography of weave architectures with tow detail

- 12-ply, dry weave
- 12-ply, infused weave

Detailed Simulations of Porous Materials

Computed Permeability

Opens the possibility of computational materials design

Credits: Panerai & Ferguson (AMA&STC/ARC), Levin (University of Illinois)
…To Enable Vehicle Scale Material Models

We want to go from here:

TPS Material

Structure

To here:
First full-scale MSL tiled heatshield simulation using PATO

Credit: Meurisse (STC/ARC)

Temperature field at the MSL surface after 70s entry

Recession of the MSL PICA heatshield after 70 sec entry, showing *fencing* phenomenon

Credit: Meurisse (STC/ARC)
Addition of water adsorbed in TPS increases in-plane (+40%) and thru-thickness (+60%) conductivity. Latent heat of fusion delays heating rate.

Result is much better agreement to MEDLI flight data.
Computational Material Design

- Long term goal: New tool for virtual material generation, focused on woven fabrics and textiles
  - Woven materials bring new challenges for modeling (increased reliance on test data)
  - However, they also provide the potential to engineer tailored materials with desired properties
  - Have demonstrated predictive accuracy for multiple properties based only on tomography and constituent data

- Integrate optimization and robust UQ techniques to optimize material architecture
- Build & test materials based on optimization outputs and validate design predictions
- Expand capability to reliability modeling and failure mode prediction

Credit: Mansour (NASA ARC)
It Takes a Village

U. of Minnesota
GSI (AFOSR)

Montana State
TPS Testing (ESI)

SRI
Side-Arm

NASA ARC

Lawrence Berkeley
Advanced Light Source

Stanford
SNSF Testing

UC Santa Cruz
PATO (STRG)

Raytheon
Ablation Workshop

Sandia
TPS Testing
Future Collaboration

Michigan
TPS Modeling (ESI)

NASA JSC
CHAR
Avcoat Modeling

U. Vermont
TPS Testing (EPSCOR, ESI)

U. Mass - Lowell
TPS Testing (STRG)

NASA LaRC
HyMets Testing

U. Illinois
TPS Modeling (ESI)

U. Kentucky
Ablator Modeling (EPSCOR, ESI)

International:
Von Karman (TPS modeling)
DLR (dusty flows)

Coming Soon To Universities Near You:
“Predictive Modeling of TPS Thermostructural Behavior”
Currently under review in STRG; award(s) anticipated in late 2017
ESM Future Directions

• **Focused** research in four elements (chosen from feedback by missions on their needs)
  – Predictive Materials Modeling
  – Shock Layer Kinetics and Radiation
  – Computational and Experimental Aerosciences
  – Guidance, Navigation and Control

• Deliver new capabilities that have advocacy and mission impact

• Continue tight collaboration with NASA programs, other government agencies, academia, and international partners
Questions?