Overview of STMD’s Investments in Advanced Entry, Descent and Landing (EDL)

6th Ablation Modeling Workshop
UIUC

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Introduction

• NASA’s technology investments are made to enable and improve multiple exploration missions.
  – Robotic – largely competed, driven by the Science Decadal Surveys
  – Human – largely directed (increasing commercial options), driven by the Human Exploration Mission Classes

• Entry, Descent and Landing (EDL) is a key challenge for most planetary lander and Earth return missions (see Roadmap TA-09)

• STMD’s main investments in EDL currently include:
  – Hypersonic Inflatable Aerodynamic Decelerators (HIAD) *
  – Adaptive Entry and Placement Technology (ADEPT) *
  – Low-Density Supersonic Decelerators (LDSD)
  – Propulsive Descent Technologies (PDT)
  – Heatshield for Extreme Entry Environments Technology (HEEET) *
  – 3-D Woven materials for Orion compression pads (3D-MAT) *
  – Conformal, Ablative Thermal Protection Systems (CA-TPS) *
  – EDL Instrumentation (MEDLI, MEDLI2) *
  – Hypersonic computational modeling and advanced materials (ESM) **

* Indicates users of advanced ablation models
Entry Systems for Human Mars Missions

- **1970’s Viking era technology is “broken” beyond MSL-sized spacecraft**
  - Rigid aeroshells constrained by launch shrouds cannot provide enough surface area to slow down a human-scale Mars lander (40,000 kg, 8 x 8 x 20 m)
  - Parachute technology (size and material) is too limited to apply
  - Can only access 30-40% of Mars—currently need to land below “sea level”

**STMD is investing in entry systems to enable Human Mars missions**

**Hypersonic Inflatable Aerodynamic Decelerator (HIAD)**
- Inflatable tori with overlaid Thermal Protection System
- Flight tested at 3 m scale (IRVE-II,3)
- ~TRL 4 for human scale

**Both systems are folded for launch and deployed before Mars entry, providing the essentially rigid aerodynamic surface and heating protection needed for hypersonic deceleration, at a scale of 25-30 m.**

**Adaptive Deployable Entry and Placement Technology (ADEPT)**
- Mechanically-deployed structure with carbon fabric “skin”
- 2-m laboratory article complete
- ~TRL 2 for human scale

**FUTURE: 25 m lands 40,000 kg**

TODAY: 4.5 m lands 900 kg
Heatshield for Extreme Entry Environments Technology (HEEET)

- Planetary Decadal Survey (2013-2023) calls for lander/probe missions to Venus and Saturn, and Earth return capsules, requiring robust TPS solutions.
- Heritage carbon phenolic has supply and industry capability challenges; is inefficient and has failure modes for these demanding conditions.
- **HEEET leverages the U. S. textile industry to utilize 3-dimensional woven materials as the base for a new, tailorable, and more robust TPS**

Project Goal: TRL6 by end of FY17 for Discovery mission infusion
Current NASA ablative heatshield designs require either high part count or extreme touch labor

- MSL required 123 PICA tiles with gap filler; Low strain-to-failure properties of PICA precluded its use on Orion

NASA has developed a new, carbon felt-based conformal high strain-to-failure thermal protection material at NASA Ames Research Center.

Conformal ablator definition

- Based on a flexible reinforcement (felt) which allows for large geometry segments (broad goods)
- Drape-able or formable during processing for easy integration which provides lower thermal conductivity in complex curved regions
- Favorable/improved strain-to-failure over PICA

Current project by end of FY15 will:

- Scale up to ~1-m sizes for backshell or ADEPT use
- Transfer basic technology to private company for low-cost small probe production.
MEDLI and MEDLI2: Mars Entry, Descent and Landing Instrumentation

• MEDLI on MSL consisted of 7 pressure ports, 7 thermocouple and char sensor plugs, with the support electronics—all on the heatshield
• Results:
  - Verified hypersonic vehicle aerodynamics, independently reconstructed density and winds
  - Verified stagnation heating; sensed turbulent heating onset time and levels; indicated recession <0.1” at measured locations.

• MEDLI2 has been approved for refly on Mars 2020, including backshell instrumentation:
  - 6 of the 7 heatshield pressure transducers calibrated for greater supersonic accuracy to resolve axial force coefficient
  - 1 backshell pressure measurement
  - 11 thermal plug locations on the heatshield
  - 9 backshell thermal plugs
  - Evaluation of 1-2 heat flux sensors on backshell, and COMARS+ sensor from DLR
  - Upward-looking parachute camera

The MSL heatshield falls away from Curiosity: 8/6/2012
MEDLI measurements successfully completed!
• What you have seen are a series of single-focus mid-TRL technology maturation projects.
• There is one additional Project, Entry Systems Modeling (ESM) that is chartered with lower TRL model and material development
• Some current investment areas are summarized on the following charts
US3D Development

• **OBJECTIVE:** Release US3D to NASA in a form capable of meeting research and production requirements of NASA flight projects

• **APPROACH:** Eliminate modeling gaps in US3D software and verify accuracy within 5% of DPLR

• **IMPACT:**

  Low dissipation flux algorithm enables high fidelity wake simulation
  Support for structural and material response coupling
  Modern software engineering
  Support for unstructured grid architecture

• **MAJOR ACCOMPLISHMENTS:**
  ✓ Code has been “completed” and delivered to NASA for project use
  ✓ Remaining work on surface boundary conditions, bug fixes is in progress
  ✓ Added support for dynamic simulations: Structural and material response coupling

Transonic wake of ADEPT concept
Advanced flux reconstruction with extremely low numerical dissipation allows US3D to resolve spatial and time scales in highly unsteady flows.
OBJECTIVE: Collect data for validation and improvement of shock layer radiation models for CO₂/N₂ and Air atmospheres

APPROACH: Databases of absolute spectral radiance as a function of position are created for shocked gases at varying pressures, velocities, and mixture ratios.

IMPACT:

* Unique facility (EAST) produces critical database for model validation
* Greatly reduced uncertainty levels (Reduction from 250% to 15% for Eq. Air)
* Improved understanding of MEDLI dataset

ACCOMPLISHMENTS TO DATE:

- Measurements verifying significant presence of mid-IR CO₂ bands at flight conditions, with preliminary impact to MEDLI.
- Proof-of-concept data and initiated upgrade of 24” Low Density Shock Tube: Will enable database extension to pressures of relevance to HIAD/ADEPT.

PLANS

- Complete refurbishment of LDST for low density testing (09/15)
- Low density Mars/Venus radiation database, including kinetic rate data (FY16)
• **OBJECTIVE:** Conduct testing of CO$_2$-based conditions in CUBRC LENS-XX expansion tunnel

• **APPROACH:** Measure pressure and heat flux on a scale MSL configuration; compare with data from conventional tunnels and CFD.

• **IMPACT:**
  - Provide comprehensive measurements in CO$_2$ using an expansion tunnel
  - Instrumentation locations & conditions tailored to better understand MEDLI data
  - Improve CFD models using new data

• **ACCOMPLISHMENTS TO DATE:**
  - First round (17 shots) in LENS-XX plus CFD analysis & planning for 2$^{nd}$ year testing.
  - Grant in place to obtain second source data from UIUC (Austin)

• **PLANS**
  - Complete second year of testing at LENS-XX (03/15)
  - Evaluate UIUC facility and determine utility for second source (06/15)
  - Improved turbulent aeroheating data for CO$_2$ atmospheres (FY16)
**OBJECTIVE:** Obtain global aeroheating data on blunt body entry vehicles with distributed roughness in CO\(_2\) *in free-flight*.

**APPROACH:** Thermally image roughened sphere-cones in the HFFAF ballistic range.

**IMPACT:**
Test series constitutes the only available distributed roughness aeroheating data for blunt bodies in CO\(_2\). Data will be used to construct correlations of roughness heating augmentation.

**MAJOR ACCOMPLISHMENTS:**
- Completed 14 runs on a series of models with parametrically varied roughness height, roughness diameter, and Reynolds numbers.
- Paper summarizing test data prepared for AIAA SCITECH conference (Jan’14)
OBJECTIVE: Develop a new first-principles volumetric ablation code, with validation

APPROACH: Cooperative Agreement in partnership with STRG for the development of PATO. NASA focused on validation as well as incorporation into a design-level code.

IMPACT:
First of its kind ablation model, and first significant SOA improvement in 40+ years may have large impact on uncertainty and design margins applied
Primary hindrance to model advancement, “it can’t be validated” demonstrated wrong with out of the box thinking.

ACCOMPLISHMENTS TO DATE:
✓ PATO V1.1 released via Academic Release
✓ Validation experiments performed at LBNL Advanced Light Source. 3D imagery of ablator substrates and in-situ oxidation.
✓ Experiments at Montana State to look at finite-rate pyrolysis products.

PLANS
✓ Final PATO release (4/15)
• **OBJECTIVE:** Develop a second generation “erosion resistant” conformal ablator.

• **APPROACH:** Explore alternate substrates, needling densities, and resin systems, evaluate performance via screening tests in HyMETS.

• **IMPACT:**

Conformal systems are a potentially game changing TPS for many applications. Having a family of potential materials, with tailorable qualities, maximizes potential for eventual mission application.

• **ACCOMPLISHMENTS TO DATE:**
  ✓ Delivered Conformal 1R system.
  ✓ Successfully produced “fluffy” structure with cured Cyanate-Ester resin and demonstrated infiltration into Morgan felt substrate.

• **PLANS**
  ✓ Define Low and High density conformal ablators (11/14)
  ✓ Determine applicability of low density system for backshell applications (FY15)
• **OBJECTIVE:** Develop a flexible TPS system capable of withstanding 50 W/cm² peak heating and flight relevant heat loads

• **APPROACH:** Multi-layer system with SiC at the surface, backed by insulators to protect the gas barrier and maintain backface temperature. Performance verified in arc jet

• **IMPACT:**
  - Potentially enables the use of HIADS in actual mission scenarios
  - Multilayer concept assures ready tailorability to multiple mission profiles
  - Possible auxiliary use as a fire protection blanked

• **ACCOMPLISHMENTS TO DATE:**
  - Delivered 50 W/cm² system with demonstrated applicability at 65 W/cm²
  - First round of –ilities testing shows identical performance

• **PLANS**
  - Deliver 75 W/cm² system, with thermal model and –ilities testing (FY15)
  - Define need (if any) for additional advances beyond 75W (FY15)
• STMD also includes lower TRL investments in EDL:
  – NSTRF
  – ESI/ECF
  – SBIR/STTR
  – Small Spacecraft Demonstrations
  – Space Technology Research Grants
NASA’s Space Technology Mission Directorate is making multiple investments in advanced Entry, Descent and Landing technologies to enable future robotic and human exploration missions.

Investments span the spectrum from flight test of deceleration systems to ground testing of subsystems to improving computational analysis capabilities.

Technologies are being applied directly to upcoming robotic (Mars 2020, Discovery-13) and human (EM-1) missions or flight tests.

An effort is underway to link efforts across the TRL spectrum in order to ensure that good ideas have a maturation path.
BACKUP
**Summary:** Developing technologies to use atmospheric drag to dramatically slow a vehicle as it penetrates the skies over worlds beyond our own. Developing the largest-ever supersonic parachute for Mars entry.

**Highlights:**

- Successful drop test and rocket sled tests in 2012-2013, illustrating the ability of the drag devices to slow a spacecraft.
- All three supersonic deceleration devices -- two inflatable vessels and the advanced parachute system -- will be the largest of their kind ever flown at speeds several times greater than the speed of sound.
- Restores test capabilities lost after Mars Viking parachute development (1960’s-1970’s)

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**Top Left Image:** Robotic class supersonic inflatable aerodynamic decelerator prototype after rapid inflation test at China Lake

**Top Right Image:** NASA’s Low-Density Supersonic Decelerator team gathers around the “SIAD-R” at China Lake

In March 2012, NASA performed a trial run on a rocket sled test fixture, powered by rockets, to replicate the forces a supersonic spacecraft would experience prior to landing.
Propulsive Descent Technologies (PDT)

Mars EDL

Current Capability Limit: ~1t mass surface delivery (MSL)
- Viking-derived supersonic chute and retro propulsion (MSL SkyCrane)

Challenge: Enable new TRL 6 supersonic decelerator capability

Mission Applicability: Robotic/human precursors >5t

Supersonic Propulsive Descent Issues

Propulsion system startup
- One rocket engine has been started in an on-coming supersonic flow

Integrated force and moments at steady state and during startup
- Aero-propulsive interactions
- Real-gas aeroscience effects
- Engine thrust effects due to on-coming flow
- Uncertainties and design have no supporting ground/flight data or engineering basis

Project Approach for FY14-15

Acquire Flight Test Data
- SpaceX successful SRP firing 9/2013
- Upcoming SpaceX flights

Utilize Grasshopper v1.1 Flights
- Remote imagery
- Additional ground assets
- Post-flight assessment

Research, design and assessment
- Perform ground tests for flight data correlation
- Work with SpaceX on EDL concepts for future Mars architectures
- Design aeroshell separation for human-scale Mars missions

Prior Cold Gas SRP Tests

LaRC Unitary Wind Tunnel

CFD
The 6 compression pads in the Orion heatshield function both structurally in the vehicle stack and thermally upon entry. Current 2D carbon phenolic pad design is complex and has issues beyond LEO return conditions. STMD is leveraging 3-D woven materials work to redesign a better compression pad that will endure through Lunar return missions.

Woven-TPS-based approach is higher strength, has better thermal performance than current materials.

Project Goal: Deliver technology at TRL 4 to Orion by mid-2014 for infusion into 2017 EM-1 flight test.
• **OBJECTIVE:** Release FUN3D to NASA in a form capable of meeting research and production requirements of all NASA flight projects

• **APPROACH:** Eliminate modeling gaps in FUN3D software and verify accuracy within 5% of LAURA

• **IMPACT:**

  Improved Speed and Numerical Accuracy
  Modern software engineering
  Support for multi-dimensional flux reconstruction to improve accuracy on unstructured meshes

• **MAJOR ACCOMPLISHMENTS:**
  ✓ Code has been “completed” and delivered to NASA for project use
  ✓ Working with projects to ensure seamless transfer

**US3D and FUN3D will be used by EVERY future NASA mission with an atmospheric entry**
• **OBJECTIVE:** Improve accuracy of DSMC models and explore development of next-generation software platform

• **APPROACH:** Create an object-oriented research platform for development of new phenomenological and physical models

• **IMPACT:**

  Improve modeling of internal energy relaxation to enable realistic high speed and reacting plume simulations

  Rapid development and validation of new models via object-oriented platform

  • **ACCOMPLISHMENTS TO DATE:**
    ✓ Validated extensions to Quantum-Kinetic model for vibrational energy relaxation; paper presented at AIAA Thermophysics Conference
    ✓ Demonstrated single processor efficiency comparable to DAC

  • **PLANS**
    ✓ Verification of parallelized DSMC code (09/30/15)
    ✓ Next gen. DSMC software delivered to line organization for production use (FY16)
OBJECTIVE: Prepare HyperRad for release to NASA in a form capable of meeting research and production requirements of all projects currently supported by NEQAIR and HARA

APPROACH: V/V of code against NEQAIR, HARA, and experiments. Introduce new models with emphasis on physical realism.

IMPACT:
- Improved predictive accuracy
- Benchmark simulations for uncertainty estimation

MAJOR ACCOMPLISHMENTS:
- Delivered equilibrium radiation version with new model of Stark broadening.
- Developed preliminary non-equilibrium analysis module that introduces new constraints on the Quasi-Steady-State (QSS) minimization problem.

PLANS
- Deliver production version (09/30/14)
• **OBJECTIVE:** Develop spectroscopic databases necessary for modeling of radiation

• **APPROACH:** First principles calculations of potential energy surfaces and collisional processes to determine key spectral lines and kinetic rates along with collision cross-sections for transport modeling

• **IMPACT:**

Spectroscopic data are crucial for accurate modeling of radiation

Kinetic rates and collision cross-sections are crucial for accurate modeling non-equilibrium

• **ACCOMPLISHMENTS TO DATE:**

  ✓ Database for triatomic molecules (of relevance for ablation products) complete

  ✓ Electron impact excitation cross section database begun

• **PLANS**

  ✓ Journal paper summarizing new kinetics and transport models (06/30/15)

  ✓ First detailed spectroscopic database for ablation products (FY16)
• **OBJECTIVE:** Evaluate models of shock layer radiation using experimental data and to quantify model uncertainties

• **APPROACH:** Models are assessed against experimental data, uncertainties are quantified, and, where possible, models are improved to minimize error.

• **IMPACT:**

Quantifiable uncertainty directly influences margin policy

Improved models reduce uncertainty & margin, and thereby reduce TPS mass

• **ACCOMPLISHMENTS TO DATE:**

  ✓ Updated chemical kinetics model for CO₂ atmospheres.
  ✓ Release of NEQAIR v13.2 with updated databases and parallel execution.
  ✓ Preliminary assessment of backshell radiation and impacts to InSight mission.

• **PLANS**

  ✓ CFD analysis of EAST flowfield to further reduce uncertainties (06/30/15)
  ✓ Detailed assessment of radiation impact on MEDLI 1 & 2 flight data (FY16)

The percent difference between NEQAIR, HARA, HyperRad low-fidelity (iStark=0), HyperRad high-fidelity (iStark=2) and EAST from 9.8 to 16 km/s.
• **OBJECTIVE:** Obtain global aeroheating data on blunt body entry vehicles with parametrically prescribed distributed roughness

• **APPROACH:** Scale models of MSL and Orion are parametrically roughened and treated with thermosensitive paint which can then be imaged to deduce global heating patterns during a test

• **IMPACT:**

  Test series constitutes some of the only openly available distributed roughness aeroheating data for blunt bodies
  Data will be used to construct correlations for roughness heating augmentation

• **ACCOMPLISHMENTS TO DATE:**
  ✓ Completed 112 runs on a series of models with parametrically varied roughness height, roughness diameter, and Reynolds numbers.
  ✓ Additional tests planned in FY14 using LaRC IR&D funds.

• **PLANS**
  ✓ Complete data analysis of LAL and HFFAF data and update turbulence models as required (09/30/15)
  ✓ Updated models for heating augmentation on blunt bodies due to roughness (FY15)
**OBJECTIVE:** Review, evaluate, and improve hypersonic turbulent heating analysis procedures as they pertain to current and future NASA mission needs.

**APPROACH:** Compile historical database and perform parametric sensitivity analyses

**IMPACT:**
- Improved understanding of wall heating and pressure sensitivities to free-interaction parameters
- Downstream influence on development of new turbulence models for hypersonic boundary layers

**MAJOR ACCOMPLISHMENTS:**
- JSR paper and NASA TM (with DVD) for 2D Shock Wave Turbulent Boundary Layer Interaction produced.

**PLANS**
- Second NASA TM for 3D SWTBLI interactions in production
**OBJECTIVE:** Revolutionize EDL systems engineering analysis. Enable rapid injection of high fidelity analysis into Phase-A mission design

**APPROACH:** Web-based MDO integration of EDL SE disciplines into a single system with tailorable fidelity based on user requirement

**IMPACT:**
Rapid EDL system analysis and design; greater fidelity in proposal and Phase-A mission designs
Consistent approach for new technology evaluation and proposal analysis

**ACCOMPLISHMENTS TO DATE:**
✓ Planned release of Phase-1 product tailored to Earth sample return on schedule

**PLANS**
✓ Add support for additional OML and TPS concepts, including HEEET (06/30/15)
✓ Release Phase-2 M-SAPE tool (FY15)
• **OBJECTIVE:** Tightly couple an ARM to CFD and demonstrate functionality

• **APPROACH:** Develop generic “handler” code via LibMESH that allows for any ARM to be coupled to any CFD code. Demonstrate and downselect to most promising combinations

• **IMPACT:**
  Coupling has long been considered important for reduced uncertainty levels
  Capability will eventually be bundled with DPLR and other CFD code releases
  Immediate benefit to MEDLI data analysis, should be markedly better than “SOA” approach in use by post-flight team

• **ACCOMPLISHMENTS TO DATE:**
  ✓ 2D tightly coupled code delivered

• **PLANS**
  ✓ Deliver 3D methodology, validated with arc jet and MEDLI data (09/30/15)
  ✓ Complete documentation and deliver code to performing org (FY16)