An Overview of EDL Investments in the NASA Fundamental Aeronautics Program

Interplanetary Probe Workshop 6

Juan J. Alonso

NASA Fundamental Aeronautics Program

June 23, 2008
Aeronautics Programs

**Fundamental Aeronautics Program**

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to enable revolutionary changes for vehicles that fly in all speed regimes.

**Aviation Safety Program**

Conduct cutting-edge research that will produce innovative concepts, tools, and technologies to improve the intrinsic safety attributes of current and future aircraft.

**Airspace Systems Program**

Directly address the fundamental ATM research needs for NextGen by developing revolutionary concepts, capabilities, and technologies that will enable significant increases in the capacity, efficiency and flexibility of the NAS.
**Aeronautics Programs**

**Fundamental Aeronautics Program**
- Subsonic Fixed Wing
- Subsonic Rotary Wing
- Supersonics
- Hypersonics

**Aviation Safety Program**
- Integrated Vehicle Health Management
- Integrated Resilient Aircraft Control
- Integrated Intelligent Flight Deck
- Aircraft Aging & Durability

**Airspace Systems Program**
- NextGen - Airspace
- NextGen - Airportal

**Aeronautics Test Program**
- Ensure the strategic availability and accessibility of a critical suite of aeronautics test facilities that are deemed necessary to meet aeronautics, agency, and national needs.
NASA Fundamental Aeronautics Program

- **Hypersonics**
  - Fundamental research in all disciplines to **enable very-high speed flight** (for launch vehicles) and **re-entry into planetary atmospheres**
  - High-temperature materials, thermal protection systems, advanced propulsion, aero-thermodynamics, multi-disciplinary analysis and design, GNC, advanced experimental capabilities

- **Supersonics**
  - Eliminate environmental and performance barriers that prevent **practical supersonic vehicles** (cruise efficiency, noise and emissions, vehicle integration and control)
  - Supersonic deceleration technology for **Entry, Descent, and Landing** into Mars

- **Subsonic Fixed Wing (SFW)**
  - Develop revolutionary technologies and aircraft concepts with highly **improved performance** while satisfying **strict noise and emission constraints**
  - Focus on **enabling technologies**: acoustics predictions, propulsion / combustion, system integration, high-lift concepts, lightweight and strong materials, GNC

- **Subsonic Rotary Wing (SRW)**
  - Improve **civil potential of rotary wing vehicles** (vs fixed wing) while maintaining their unique benefits
  - Key **advances** in multiple areas through **innovation** in materials, aeromechanics, flow control, propulsion
Hypersonics Project

Highly Reliable Reusable Launch Systems

- Materials & Structures
  - Thermal Protection Systems
  - Hot Structures
  - High Temperature Seals

- Airframe-Propulsion Integration
  - Integrated Vehicle Performance
  - Inlet Boundary Layer Ingestion
  - Nozzle Performance

- Propulsion
  - High-Mach Turbojets
  - Dual-Mode Scramjets
  - Combined Cycle Engines

Integrated Systems
- Staging
- Thermal Management
- Power and Actuators
- Intelligent Controls

High Mass Mars Entry Systems

- Bow shock
- Boundary layer
- Viscous interaction
- Surface recombination
- Radiation
- Dissociation-ionization
  (thermochemical non equilibrium)
- Transition to turbulent
- Ablation
- Shock-shock interaction
- Reaction control plumes
- Control surface
- Flow separation
- Shear layer
- Impingement (reattachment)

Similar technologies needed for both applications

Conduct fundamental and multidisciplinary research to enable airbreathing access to space and entry into planetary atmospheres
Supersonics Project

Project Goal: Tool and technology development for the broad spectrum of supersonic flight.

Supersonic Cruise Aircraft
Eliminate the efficiency, environmental and performance barriers to practical supersonic cruise vehicles

High Mass Planetary Entry Systems
Address the critical supersonic deceleration phase of future large-payload Exploration and Science Missions
Brief Summary of High-Speed Research Activities

QuickTime™ and a H.264 decompressor are needed to see this picture.
### Mars Heritage Aeroshell Comparisons

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter, m</td>
<td>3.5</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
<td>4.5</td>
</tr>
<tr>
<td>Entry Velocity, km/s</td>
<td>4.5/4.42</td>
<td>7.6</td>
<td>5.5</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>Entry Mass, kg</td>
<td>930</td>
<td>585</td>
<td>840</td>
<td>602</td>
<td>3250</td>
</tr>
<tr>
<td>Peak Heat Rate, W/cm²</td>
<td>24</td>
<td>106</td>
<td>48</td>
<td>56</td>
<td>150</td>
</tr>
<tr>
<td>Nominal α, deg</td>
<td>-11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-16</td>
</tr>
<tr>
<td>Nominal L/D</td>
<td>0.18</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.24</td>
</tr>
<tr>
<td>Control</td>
<td>3-axis</td>
<td>Spinning</td>
<td>Spinning</td>
<td>3-axis</td>
<td>3-axis</td>
</tr>
<tr>
<td>Guidance</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Development Areas for Technologies and Tools

Exo-Atmospheric Approach

- Radiative heating / turbulence
- Coupled ablation
- Aftbody heating
  - TPS advancements / warm and hot structures
  - Deployable/inflatable aeroshells (exo-atmospheric deployment)
- Alternate shapes
- Guidance & controls
- Angle-of-attack modulation
- Aero / RCS interaction
- Instrumentation

Hypersonic Entry

- Unsteady aftbody flow mitigation/control
  (via PASSPORT technology?)
- Deployable/inflatable supersonic decelerators
- Supersonic propulsion
- Pinpoint landing
- Hazard detection & avoidance

Supersonic Descent

Subsonic Landing

Blue text indicates current FA activity
Current ARMD EDL Investments

- Materials and structures (TPS is subset)
- Fundamental flow physics
- Mars Architecture Working Group EDL trades (Mars entry and Earth return) — ARMD, ESMD partnership
  - Inflatable Aerodynamic Decelerators (IADs)
    - Inflatable Reentry Vehicle Experiment (IRVE)
    - Program to Advance Inflatable Decelerators for Atmospheric Entry (PAI-DAE) — ARMD, ESMD, IPP partnership
- Supersonic retro propulsion
- Mars Science Laboratory (MSL) EDL Instrumentation (MEDLI) — ARMD, ESMD, SMD partnership
- Lunar reEntry eXperiment (LE-X) — ARMD, ESMD partnership
- High-Mass Mars Entry Systems (HIMMES) NRA
Motivation for Deployable Hypersonic Aeroshells

4.57-m Rigid Aeroshell

15-m Inflatable Aeroshell

Ballistic Entry (6 km/s),
2200 kg Entry Mass,
70-deg Sphere-Cone

Heat Rate W/cm² vs. Altitude, km

Heat Rate W/cm² vs. Mach
Motivation for Supersonic Decelerators

Drag: Parachutes vs. Inflatables

Advantages over parachute
- No transonic drag bucket
- Higher $C_D$
- $C_D$ maintained as $M$ increases
- Directionally stable
- Reduced multi-body motion
**PAI-DAE Project Highlights**

**Aerodynamics & Deployment Testing:**
- GRC 10x10 Facility
- LaRC Unitary Facility
- Model Concept: Tension Cone

**Ballistic Range Test Matrix:**
- Tests w/ variations in half-angle, shoulder radius, & aftbody aspect ratio

---

**Surface Pressure**

**Heat Flux**

**8' HTT Test Sled Design**

**8' HTT Coupon Holder Design**
Present Research

Objectives: Characterize the aerodynamic and structural performance of tension cone IADs

   Validate CFD, FEA, and FSI codes for use in the analysis and design of tension cone IADs

4 x 4 ft Unitary Wind Tunnel Test Program
- Rigid models
- Surface pressures and force/moment
  - 1.65 ≤ M ≤ 4.5
- Aerodynamic performance
- CFD validation

10 x 10 ft Supersonic Wind Tunnel Test Program
- Inflatable and semi-rigid models
- Force/moment, deployment, reqd. inflation pressure
  - 2.0 ≤ M ≤ 2.5
- Aerodynamic and structural performance
- CFD, FEA, and FSI validation
Models

General Configuration

- 60° tension cone attached to a 70° Viking-type forebody
- 0.6 m (~ 2 ft) total diameter
- Torus approximated by a 16-sided polygon
Models (cont.)

Semi-Rigid Model
- Textile tension shell attached to a rigid torus
- Used to characterize aerodynamic and structural behavior while avoiding deployment and inflation complications

Inflatable Model
- Textile tension shell attached to a textile inflatable torus
- Used to characterize deployment dynamics and required torus pressures
Model Deployment
Data from the AOA sweeps will allow us to determine the static aero coefficients: $C_A$, $C_N$, and $C_m$.

We will be able to perform a direct comparison between the $C_A$, $C_N$, and $C_m$ values from this test and the 4 x 4ft Unitary test.
Preliminary Findings and Observations

- Aerodynamic inflation peak load does not overshoot its static value (i.e., $q_{C_D,S}$). Thus, calculating this peak load should be relatively simple.

- Adding anti-torque panels reduces the required torus inflation pressure and increases the drag coefficient.

- Minor wrinkling of the torus does not reduce the tension cone's drag coefficient. The torus internal pressure does not need to be so high as to remove all wrinkles.

- Supersonic flow is stable around a properly designed tension cone.

- The torus remains almost perfectly aligned with the aeroshell at angles of attack up to 18 degrees.

- Collected data should allow us to calibrate CFD, FEA, and FSI models.
IRVE Mission Timeline

- Launch on Terrier-Orion from Wallops Island
- Terrier burnout, 7 s
- Orion ignition, 15 s
- Orion burnout, 40 s
- Coast to 75 km (60 s) and separate from Orion
- Separate RV TM/NC assembly from payload shroud, 70 s. RV begins broadcast of data.
- Separate RV from TM/NC, 80 s
- Inflation begins at 290 s
- RV attains shape prior to 125 km
- t = 320 s, h = 125 km
- RV passes through pressure pulse at ~46.7 kilometers.
  - t = 384 s or
  - h < 46.7 km
- Flight Experiment concludes after vehicle has passed max dynamic pressure.
- WFF provides launch operations, telemetry acquisition, radar track
IRVE Flight Instrumentation

- Aeroshell structural dynamics (photogrammetry results)
- Flight path data products
  - Trajectory reconstruction
  - Angle-of-attack history
  - $C_A$ history
- In-depth & radial aeroshell temperature distribution
- Housekeeping data products
  - Inflation system tank temperature & pressure
  - Aeroshell bladder pressures
  - Ambient pressure
  - Transmitter temperatures
  - Voltages
Overview

MEDLI is an instrumentation suite to be installed in the heatshield of the Mars Science Laboratory’s (MSL) Entry Vehicle that will gather data on its aerothermal, aerodynamic, and thermal protection system (TPS) performance, as well as atmospheric density and winds, during entry and descent, and will provide engineering data for all future Mars missions.

Aerothermals & TPS
- Verify transition to turbulence
- Determine turbulent heating levels
- Determine recession rates and subsurface material response of ablative heatshield at Mars conditions

Aerodynamics & Atmospheric
- Determine density profile over large horizontal distance
- Determine wind component
- Separate aero from atmosphere
- Confirm aero at high angles of attack
MEDLI Consists of Three Main Subsystems

- **MEDLI Instrumented Sensor Plug (MISP)**
  - A plug consists of 1.3” diameter heatshield Thermal Protection System (TPS) core with embedded thermocouples and recession sensors
  - Each plug consists of 1 recession sensor and 4 thermocouple sensors

- **Mars Entry Atmospheric Data System (MEADS)**
  - Series of through-holes, or ports, in TPS that connect via tubing to pressure transducers

- **Sensor Support Electronics (SSE)**
  - Electronics box that conditions sensor signals and provides power to MISP and MEADS
Mars Orbit Insertion (MOI):
Aerocapture vs. All-Propulsive Insertion Trade

- Propulsive capture
  - Large $\Delta V$ (large propellant mass requirements)
  - Higher IMLEO
- Aerocapture (e.g. via “ellipsled / dual-use launch shroud”)
  - $\Delta V$ requirement is slashed
  - Not flight tested for large payloads
  - Increased structural volume may take away from payload volume
  - Mass savings need to be confirmed
- Aerodynamic and Aerothermal challenges
Mission Objective: Obtain unique flight data for basic flow physics and Mars entry technology

Cost-sharing partners:
NASA
ATK

Projected launch date: July 2008
HyBoLT Pre-flight Testing

- Pre-flight testing of HyBoLT Side B (forced transition) in LaRC Mach 6 Wind Tunnel (Re 7M) completed. HYP.04.04.002 (HyBoLT post-flight data analysis)

- Fabrication of HyBoLT Side A (natural transition) models for post-flight data analysis is underway. HYP.04.04.002 (HyBoLT post-flight data analysis)
Unsteady Afterbody Heating

Unsteady turbulent heating in the leeside has been identified as an issue recently because of large uncertainties associated with cavities and blowing.

Implementation of a time-accurate dual time stepping scheme into DPLR RANS code completed HYP.04.03.017 (Lunar return vehicle with ablation product blowing)
Current practice of computing radiation in an uncoupled manner leads to overestimation of total heating. Coupling (HARA + LAURA) method validated against Stardust data.  HYP.04.03.017 (Lunar return vehicle with ablation product blowing)
Thermal Protection System (TPS) Taxonomy

Thermal Protection System
Aeroshell (heat shield, insulator, structure) of a vehicle which protects payload from aerothermal loads encountered during atmospheric entry

Single Use (HMMES)
TPS designed for a single mission with expendable materials.

- **Ablators (>3000°F)** ESMD, SMD, ARMD
  Dissipation of heat through melting, pyrolysis charring, and sublimation. Results in loss of material and shape.

- **Ceramic Composites (<3500°F)** ESMD, ARMD
  Dissipation of heat by means of radiation and sublimation. Results in modest loss of material and shape.

- **Deployable TPS (<1000°F)** ARMD
  Flexible fabrics and films for inflatable and mechanically-deployed decelerators.

Multiple Use (HRRLS)
TPS designed for several missions without loss in performance.

- **Metals (<2000°F)** AFRL
  Dissipation of heat through radiation and heat sink. High mass penalty to vehicle.

- **Ceramic Composites (<3000°F)** ARMD, AFRL
  Dissipation of heat by means of radiation. Results in loss of material property but retained shape and function.

- **General (<2000°F)**
  AETB, thermal blankets, and thermal felts. High maintenance systems that add additional weight to the vehicle.

Deployable TPS (<1000°F) ARMD
Flexible fabrics and films for inflatable and mechanically-deployed decelerators.
Phenolic Impregnated Carbon Ablator (PICA)

- PICA is baseline TPS for Orion (resurrected Avcoat is also being considered) and MSL heat shields
- Flight heritage on Stardust (although not tiled)
  - Orion driver: Lunar direct return conditions (Peak heat flux: \(~1000\) W/cm\(^2\))

ARMD Hypersonics current research support performance objectives
- Improve strength and reduced recession rate
- Improve thermal performance by reducing radiant heating component
CNTs are thin, tiny ropes with large surface area, high aspect ratio, and high strength (one of the most effective strengtheners for polymer composites).
6.1 EDL Trades
- Novel and innovative concepts
- Integrated elements
- System-level trade studies

6.2 Experimental Validations
- Non-intrusive diagnostics
- Flight data reconstruction
- FSI validation datasets

6.3 Fluid Dynamics
- Real gas turbulence
- Rarefied flow
- Ablation Products
- Gas surface interaction

6.4 Fluid-Structures Interaction
- Simulation tools for design
- Flexible membrane structures
- High-speed deployment

6.5 Supersonic Propulsion
- Analytical tools and methods
- Propulsive deceleration
- Reaction control systems

6.6 Materials & Structures
- Computational Modeling
- Advanced decelerator materials
- Multifunctional ablators
Summary / Conclusions

• NASA ARMD has setup a thriving research program to support EDL of future missions:
  - In-house
  - Other NASA mission directorates and OGAs
  - Academic / industrial community through the NRA

• Many advancements and significant investments are needed to bring about revolutionary changes in our current EDL capabilities

• Focus is on longer-term research and validation and verification of future tools that will be required to analyze / design such systems