Development Challenges of Game-Changing Entry System Technologies From Concept to Mission Infusion

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• Leadership and Management @ STMD, SMD, Orion/LM and NASA Centers, GCDP, SBIR Program
• Finally community support and Advocacy
  ▪ VEXAG and OPAG
Subsystem technologies for robotic and human missions
- Our development experience is in the recent NASA environment.
- Entry systems specifically, primarily the thermal protection subsystem

Discuss four technologies
- Being developed simultaneously
- Technology push from Space Technology Mission Directorate (STMD)
- Mission pull from Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD)
- Challenges during development

Observations and lessons learned may be applied to
- Space technologies other than TPS
- Organizational frameworks other than NASA.
Scientific goals and desire for human exploration enabled by technology
21st Century

Shuttle Last Flight
July 8, 2011

Asteroid Redirect
~2020?

End of Station
~2025?

Human Mars Mission

MERs
Jan 4, 2004
Jan 25, 2004

Phoenix
May 25, 2008

Curiosity
August 6, 2012

InSight
3/2016

Osiris Rex
9/2016

Mars 2020

Discovery
New Frontier

A evolvable Mars approach
2035 – 2045?

New Technology needed to enable demanding Science and Human missions
Technology Development at NASA

• Recognized that very little seed corn is left
• Bobby Braun was appointed as the NASA Chief Technologist (Feb., 2010)
• Space Technology Mission Directorate created (Feb., 2013).
  ▪ Vision: “STMD rapidly develops, demonstrates, and infuses revolutionary, high-payoff technologies.”
  ▪ “By investing in bold, broadly applicable, disruptive technology that industry cannot tackle today, STMD seeks to mature the technology required for NASA’s future missions in science and exploration while proving the capabilities and lowering the cost”
  ▪ “With Game-Changing, we’re looking at a two-year process of getting the TRL from 3-5” – GCD Program Goal

“We intend to take considerable risks' to innovate” – Bobby Braun
Decadal Survey recommended in situ Venus, Saturn and Sample Return missions

- Galileo and P-V
  - Carbon-phenolic
- MSL
  - SLA Replaced by PICA
- Orion
  - Apollo TPS revived
- Sample Return Missions
  - Robust TPS

NRC recommended investment in key technologies (e.g.: ablative TPS, conformal TPS, Deployable Entry System)
STMD Investment Strategy

Technology Development
- Game Changing Development Program
- SBIR Program Phase III

New Technology Partners
- Flight Opportunities Program
- Centennial Challenges Program

Early Stage
- NASA Innovative Adv Concepts Program
- Space Tech Research Grants Program
- Center Innovation Fund Program
- SBIR Program Phases I & II

Mid TRL

Technology Demonstrations
- Technology Demonstration Systems
- Small Spacecraft Technologies

High TRL
EDL Technology Pipeline
Game Changing Technologies

Technology Development
- Game Changing Development Program
- SBIR Program Phase III

Mid TRL
- Conformal 3-D Woven
- 3-D MAT
- HEEET
- ADEPT

New Technology Partners
- Flight Opportunities Program
- Centennial Challenges Program

Low TRL
- NASA Innovative Advanced Concepts Program
- Space Tech Research Grants Program
- Center Innovation Fund Program
- SBIR Program Phases I & II

High TRL
- Technology Demonstrations
  - Technology Demonstration Systems
  - Small Spacecraft Technologies

Technology Demonstrations
- Small Spacecraft Technologies
<table>
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<tr>
<th>Considerations for Game-Changing Development Funding</th>
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<tr>
<td>Game Changing Development Program View (May 2015)</td>
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<table>
<thead>
<tr>
<th>Appropriateness</th>
<th>Is this a broad technology and not engineering/research?</th>
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<tbody>
<tr>
<td>Relevance/Alignment</td>
<td>Is the technology aligned with Technology Roadmaps, Decadal Surveys, etc.?</td>
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<tr>
<td>Value Proposition</td>
<td>What is the ratio of the potential benefits of the technology to the cost to mature the technology?</td>
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<tr>
<td>Leveraging/Partnering</td>
<td>Is the stakeholder/partner contributing resources?</td>
</tr>
<tr>
<td>Customer Advocacy</td>
<td>Do potential end users recognize the benefit and support the activity?</td>
</tr>
<tr>
<td>Development Plan &amp; Infusion Potential</td>
<td>Is the activity well-planned, with appropriate schedule, budget, advancement milestones, KPP’s, and options?</td>
</tr>
<tr>
<td>Acquisition Strategy</td>
<td>Is the proposed acquisition strategy the most effective strategy to mature the technology?</td>
</tr>
<tr>
<td>Timeliness</td>
<td>Is it critically important that this investment be initiated right now?</td>
</tr>
<tr>
<td>Maturity</td>
<td>As a general guideline, GCD initiates investments at a TRL = 3 and matures the technology to TRL = 5.</td>
</tr>
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</table>
Conformal Ablative TPS Technology
IHF 289 1850 W/cm²
1.5 atm, 10 sec
(CPICA and ACPICA)

Recession of CPICA2 < PICA

Recession of
CPICA = ~PICA

Back face temp
CPICA = ~1/2 PICA

Compliance and Robustness
CPICA >> PICA

Conformal 1 Est.
Hyp EDL - FAP

CA250 CPICA Improved, Scale Up & Seam Design

2009 - 2011 Better PICA / SIRCA

IHF 227
1000 W/cm²
0.85 atm

2014 TVA Small Probe

2013 ADEPT Orion Back-shell

2012 Mars 2020

ESM Advanced Conformal Ablators

2015 New Frontier Orion EM3

Flight Article
3-D Woven TPS Technologies

3-D MAT, HEEET and ADEPT make use of advances made in the last decade in the Textile Industry.
2-D weaving (Fabrics that we wear).
- Composites stack 2-D woven plies to make a laminate

3-D weaving
- Adds a yarn in the Z direction
- Architectures:
  - layer-to-layer, 3-D orthogonal
- Advances in textile engineering allow different compositions & densities to be combined in a single woven preform
- Preforms can be:
  - Non-resin infused (flexible) (ADEPT Fabric)
  - Resin infused (rigid) (3-D MAT & HEEET)
Exploring the Potential in 3-D Woven TPS Technology
(Center Investment Funds and Broad Area Announcement)

- **Woven TPS** is a family ablative materials
  - **3D-MAT** (highest density) and **HEEET** (mid-density) applications are a product of the Woven TPS family

- Lower density options
  - Mass efficient and robust option for Human Mars return missions
3-D Multi-functional Ablative TPS (3-D MAT)
Technology
• 2D laminate and metallic insert of the EFT1 design not extendable
• 3-D Woven quartz composite material is simpler and meets all the loads, structural, pyro-shock and entry thermal.
• 3DMAT project addressed a material capability need for Orion by developing a 3D woven composite with robust structural and aerothermal performance
• Orion vetted 3DMAT for Exploration Missions shortly before PDR (5/15)
• Orion Program is currently producing 30 billets for EM-1 mission development and flight hardware (2018 lunar flight)
• Other aerospace companies are evaluating 3DMAT for additional missions
Heat shield for Extreme Entry Environment Technology (HEEET)
HEEET Maturation Plan and Progress

**FY'13**
- Formulation
  - Blended Yarn
  - Resin Infusion
  - Arc Jet Test
  - Architecture Finalization

**FY'14**
- TRL (3 – 6) Technology Maturation
  - Requirements
  - Acreage Performance
  - Material Prop
  - Mold/Resin Development

**FY'15**
- Thermal Resp.
  - Mold/Resin Scale-up
  - Seam Selection
  - Weave (12” x 2.1”)

**FY'16**
- MDU Build Complete
  - Seam LHEML Verification
  - Integration

**FY'17**
- ETU Build Complete
  - Valid. Arc Jet Testing
  - ETU Testing completed
  - Final Report and Docu.
3-D MAT and HEEET Development Background

3D Woven Multifunctional Ablative TPS (3D-MAT)
Enabling Orion with Lunar Capable Compression Pad

Woven TPS IR&D

Heat-shield for Extreme Entry Environment Technology (HEEET)
Tech. Maturation to enable Venus, Saturn and outer planets missions
Discovery AO Incentivized New Frontier FY’16

Robust Heat-shield for Human Missions (Future Potential)

2017+

2022+: Crew

2018: Lunar

2020 – 2024

Woven TPS GCT BAA

March 2011
Jan. 2012
June, 2012
Oct. 2013
Sept. 2017
Adaptable, Deployable Entry and Placement Technology (ADEPT)
ADEPT Background

- Original Driver - Human Mars Mission
  - Large drag area needed at Mars
  - NASA’s risk posture with HIAD
- An umbrella-like deployable, low ballistic coefficient concept with a 3-D Woven carbon fabric as a multi-functional aeroshell and TPS

23m: Mars Exploration

6m: Venus Lander

1m: “Nano” ADEPT
ADEPT Development Highlights (FY12-mid FY15)

Carbon Fabric Combined Environment Performance (FY12)
- Carbon fabric thermal and mechanical performance under relevant testing in arcjets.

2 m Ground Test Article (FY13)
- Fabric gore manufacturing & integration process at 2 m scale
- Demonstrated reliable operational functionality of the mechanical design, software control logic, and system level integration

Fabric Seam Development (FY14)
- High Strength seams designed and fabricated (ultimate tensile strength in excess of 3000 lbs/in)
- Seam arc jet test combined (aero-thermo-mechanical load) environments (100 W/cm² for 220 seconds), heat load in excess of 20 kJ/cm².
- Carbon-stitched seams are viable for the ADEPT design
- Project focus on 1m class design (nano-ADEPT) for system level testing

1m class System Testing (FY15)
- SPRITE-C Arcjet testing
- 7x10 Wind Tunnel aeroloads testing
- Sounding Rocket flight test design and maturation

Stowed
Deployed (shown w/o Fabric)
Observations and Lessons Learned
One R: Realism in estimating Maturation Time

Truly game-changing technologies with uncertain challenges have uncertain schedules

- We plan for known risks – discovery of new risks requires additional time
- Fluctuating resource commitments adversely impact maturation time line.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Planned</th>
<th>Executed</th>
<th>Comment</th>
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<tbody>
<tr>
<td>Conformal</td>
<td>2+</td>
<td>5+</td>
<td>Annual budget uncertainty and unanticipated reduction</td>
</tr>
<tr>
<td>3-D MAT</td>
<td>18 months</td>
<td>30 months</td>
<td>Technical Challenges in weaving and resin infusion</td>
</tr>
<tr>
<td>HEEET</td>
<td>4 years</td>
<td>TBD</td>
<td>Progress is on target – 2 years into a 4 year project</td>
</tr>
<tr>
<td>ADEPT</td>
<td>3 years</td>
<td>5+</td>
<td>Annual budget uncertainty and unanticipated reduction</td>
</tr>
</tbody>
</table>

- Discover challenges as early as possible through broad exploration of option space
- Progress should be measured by challenges overcome, rather than strict adherence to success-oriented schedule
- Goal of (2-3) years for GCDP Projects, while commendable, is rarely realizable. 3-D MAT is an exception, but still needed schedule extension.
Two R’s: Reward to Risk

Risk is both real and perceptual:

- EDL is inherently risky (real)
  - “Test as we Fly” and Full scale ground testing in fully relevant environment not feasible.
- New technology is assumed to have significant unknown risk (perceptual)
- Risk posture for competed vs directed mission is different (organizational factors)

Reward /Success is mission infusion

- Mission enabling technologies have higher reward (Value)
  - Interaction with mission planners and scientists crucial

<table>
<thead>
<tr>
<th>Technology Reward/Risk</th>
<th>Perceived Value At initiation</th>
<th>Current Perceived Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conformal</td>
<td>Moderate</td>
<td>High</td>
<td>Original 250 W/cm² – currently capable of 2000 W/cm² Mission Infusion – shifting focus. Future potential (Orion, NF)</td>
</tr>
<tr>
<td>3-D MAT</td>
<td>High</td>
<td>Very High</td>
<td>Targeted and timely solution. Enabler; High Risk and High Value</td>
</tr>
<tr>
<td>HEEET</td>
<td>High</td>
<td>High</td>
<td>Enabler and unique; robust system with high performance</td>
</tr>
<tr>
<td>ADEPT</td>
<td>High</td>
<td>High</td>
<td>An option for Human Mars. Mission Infusion – shifting focus. Nano-ADEPT Mission pull is TBD</td>
</tr>
</tbody>
</table>

Be transparent - Risks as well as Rewards during development are both evolving.
Three R’s to enhance Mission Infusion Success: Reference missions, Requirements and Review

Rigorous development of requirements for several targeted missions, during formulation, can prepare a technology for multiple infusion opportunities

- Engage potential missions and user community early and often
  - Capture system integration and con-ops constraints along with performance requirements
  - Review progress and current plan, at all points in development via Interdependent Review Board that includes mission infusers and stakeholders
  - Be transparent and develop trust with the user and stakeholder

<table>
<thead>
<tr>
<th>The three R’s</th>
<th>At initiation</th>
<th>Current</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conformal</td>
<td>Low</td>
<td>Moderate</td>
<td>Mission Infusion – shifting focus and emerging capability. Need to develop full set of requirements and need to establish IRB.</td>
</tr>
<tr>
<td>3-D MAT</td>
<td>High</td>
<td>Very High</td>
<td>Close workign relationship with Orion; Well defined Requirements and exit criteria</td>
</tr>
<tr>
<td>HEEET</td>
<td>High</td>
<td>High</td>
<td>Early engagement through OPAG and VEXAG and Workshop. Established Independent Review Board (IRB)</td>
</tr>
<tr>
<td>ADEPT</td>
<td>High</td>
<td>Low-Moderate</td>
<td>Early engagement with VEXAG / Goddard/JPL. HEEET as a competitor led to shifting focus. Requirements are evolving</td>
</tr>
</tbody>
</table>

Involve mission implementers from the beginning or if application focus changes and provide sufficient technical detail to inform their decision-making.
Project Execution Success: Defining TRL and Exit Criteria

- SMD experience in Technology maturation inspires caution
  - ASRG and SEP
- Who defines? Who accepts? Who owns?
  - STMD vs SMD and HEOMD; Missions/Proposal Teams; Project

<table>
<thead>
<tr>
<th>TRL/Exit Crit.</th>
<th>At initiation</th>
<th>Current</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conformal</td>
<td>High</td>
<td>Moderate</td>
<td>Clearly defined with KPPs. But KPPs were incomplete for integration</td>
</tr>
<tr>
<td>3-D MAT</td>
<td>Very High</td>
<td>Very High</td>
<td>Well defined with input from Orion. During development Orion (LM) requirements became more demanding. Met the challenge</td>
</tr>
<tr>
<td>HEEET</td>
<td>High</td>
<td>High</td>
<td>Early definition of requirements definition led to defining TRL and Exit criteria acceptable to Independent Review Board</td>
</tr>
<tr>
<td>ADEPT</td>
<td>High</td>
<td>Moderate</td>
<td>Shifting mission focus (Venus 6m; 2m ground test article; 1m nano-ADEPT) led to shifting TRL and Exit criteria</td>
</tr>
</tbody>
</table>

Document missions design, TRL/IRL/MRL and exit criteria as part of the project plan. Verify with user communities and generate a signed mission use agreement.
Partnerships for Project Execution Success

- Engage industrial partners early in development
- Mission directorates as partners – Skin in the Game
- Stakeholders as Partners -
  - NASA’s Small Business Innovative Research (SBIR) program
  - Sub-Orbital Flight Test program
  - Communities such as VEXAG and OPAG promote mission benefits
  - Leaders at NASA Centers, JPL, APL allocate resources and support reviews

<table>
<thead>
<tr>
<th>Partnership</th>
<th>At initiation</th>
<th>Current</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conformal</td>
<td>None</td>
<td>Moderate</td>
<td>TVA as a partner brings flight data but it is not the same as mission infusion as originally envisioned. NF proposers – evaluating Conformal</td>
</tr>
<tr>
<td>3-D MAT</td>
<td>High</td>
<td>High</td>
<td>Orion and SBIR - funding partners. Vendor relationship excellent.</td>
</tr>
<tr>
<td>HEEET</td>
<td>High</td>
<td>High</td>
<td>SMD support during formulation and project phase exceptional. Incentivized for Discovery Proposals by SMD (Risk assumed by NASA) Early engagement with Discovery, New Frontier and ESA M4.</td>
</tr>
<tr>
<td>ADEPT</td>
<td>High</td>
<td>Low</td>
<td>Early focus on Venus – excellent partnership and advocacy. Partnership for Nano-ADEPT needs to be identified and worked</td>
</tr>
</tbody>
</table>

Well developed and managed partnerships drive risk identification and mitigation and promote project success
Tech Maturation Execution Success: Competition improves all competitors

- Vigorous and competitive assessment of technology value can expose untested assumptions and generate new concepts
  - HIAD and ADEPT
  - ADEPT and HEEET
  - HEEET and Conformal

<table>
<thead>
<tr>
<th>Competitive Assessment</th>
<th>Uniqueness at initiation</th>
<th>Current uniqueness</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conformal</td>
<td>Moderate (Alternate to PICA)</td>
<td>High value</td>
<td>Preliminary testing shows capable of ~2 kW/cm(^2) and 1.5 atm. Potential for Orion at V &gt; 11.5 km/s with better mass savings</td>
</tr>
<tr>
<td>3-D MAT</td>
<td>Very high</td>
<td>Very High</td>
<td>Neither engineering redesign and other options did not pan out</td>
</tr>
<tr>
<td>HEEET</td>
<td>High</td>
<td>High</td>
<td>No alternate at this time with the robust and performance to meet extreme entry</td>
</tr>
<tr>
<td>ADEPT</td>
<td>High</td>
<td>High</td>
<td>Still an option for Human Mars. 2m GTA built and tested for 6m Venus application. Nano-ADEPT, once flight tested could be an enabler for small spacecraft aerocapture/entry</td>
</tr>
</tbody>
</table>

Technologists should acknowledge when competing concepts show great progress and be ready to switch focus when no longer a viable competitor.
Concluding Remarks

Technology Organizations must take the risk and make the long commitment as part of a balanced portfolio

- Genuine Game Changing Technology Development is Challenging
  - High Reward and High RISK
  - Longer development time
  - Low end-user commitment

Achieving TRL 6 is only the end of the beginning

- Game changing success is when Mission Infused - NASA’s success
  - Technology must be sustained through the mission infusion
  - Requires commitment from multiple organizations (STMD., SMD, NASA Centers, etc).
  - How to “Park” the technology once matured to TRL 6?
Very nature of “game changing” technologies have unknown risks (more so than others)

- In-depth pre-formulation
  - Can and does help with risk mitigation strategies
- Risk mitigation requires
  - Resources proportional to the complexity and the breadth of application

**Flexibility:**

- Funding cycles / constraints are shorter than technology cycles.
- Unexpected risks will emerge
- Must re-plan as often as needed
Thank you

Q?
A!