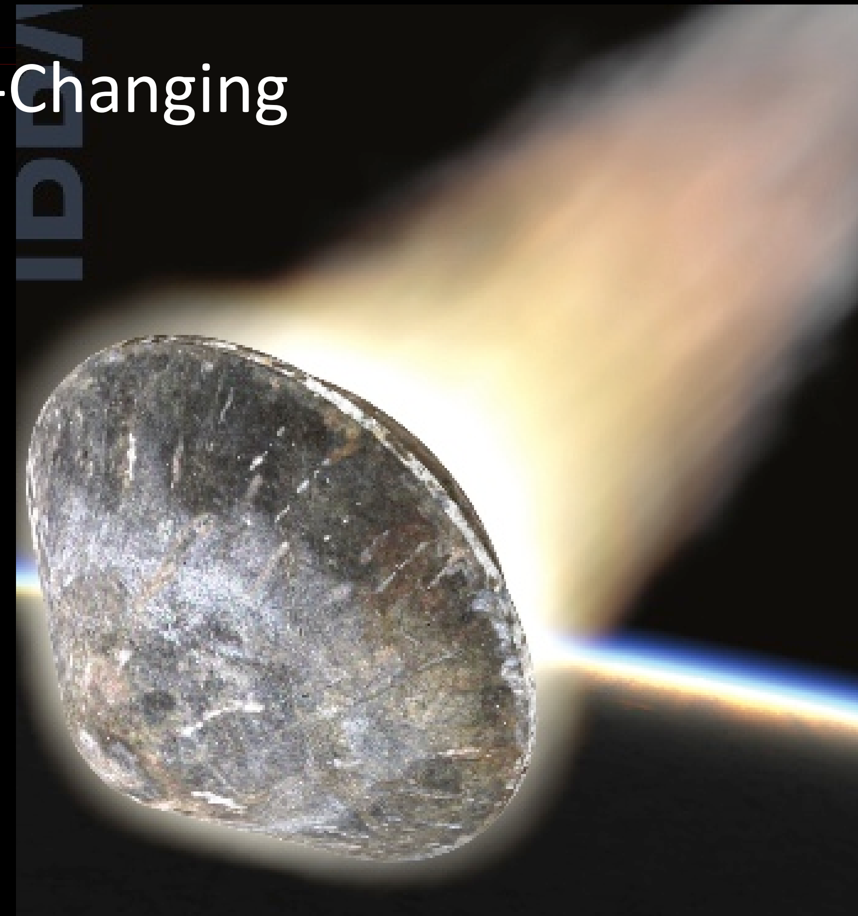
Development Challenges of Game-Changing Entry System Technologies From Concept to Mission Infusion

Ethiraj Venkatapathy
NASA Ames Re search Center

Co-Authors:
Robin Beck, Don Ellerby,
Jay Feldman, Peter Gage,
Michelle Munk and Paul Wercinski



12th International
Planetary Probe Workshop
Cologne / Köln Germany
15–19 June 2015

Acknowledgements

- There are many, many to thank and it is a long list
- First and foremost are those that address each and every technical challenge that we faced and will continue to face. These are folks at NASA Centers (Ames, Langley, JSC, Goddard, JPL, APL), and Industrial partners and Vendors(BRM, TRL, SDC, FMI,TVA)
- Test facilities and the folks that are not often visible at (JSC, ARC, AEDC, LHEML)
- Leadership and Management @ STMD, SMD, Orion/LM and NASA Centers, GCDP, SBIR Program
- Finally community support and Advocacy
  - VEXAG and OPAG

Game-Changing Entry System Technologies

- 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.

SPACE EXPLORATION & EDL TECHNOLOGIES
THE FIRST 50 YEARS

Human

JFK "To the Moon"
May 25, 1961

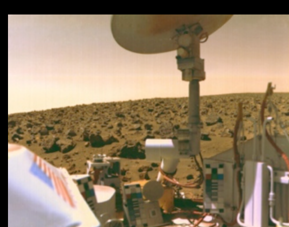
Apollo 11
July 20, 1969

Space Shuttle
April 12, 1981

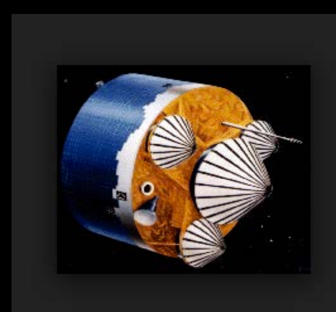
ISS: Nov. 20, 1998

Robotic Science

Viking 1 Lander
July 20, 1976



Pioneer-Venus
Arrical:Dec. 9, 1978

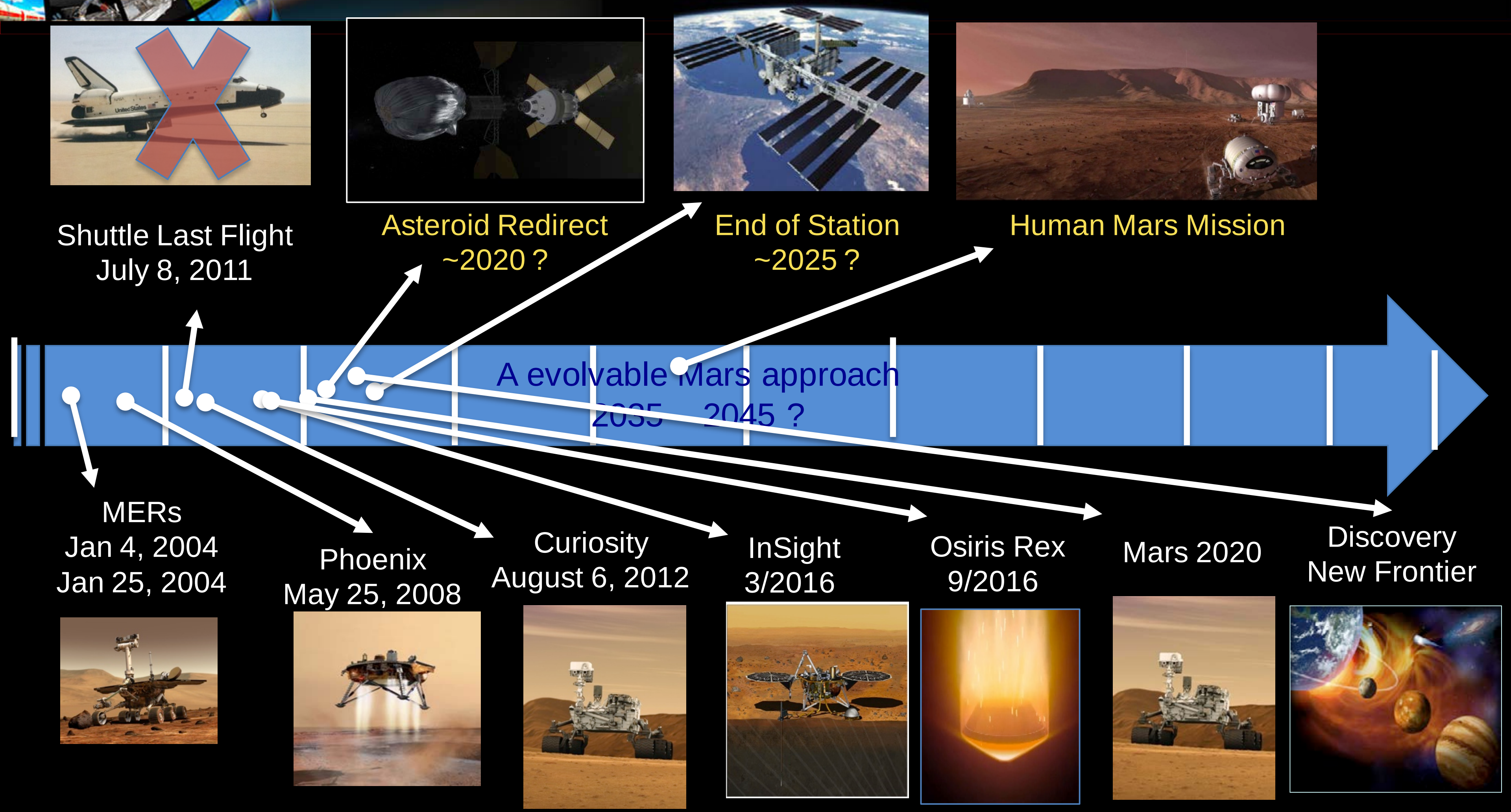


Galileo Probe
Launch: Dec. 18, 1989
Arrival: Dec 7, 1995

Pathfinder Sojourner
July 4, 1997

Scientific goals and desire for human exploration enabled by technology

21ST CENTURY



New Technology needed to enable demanding Science and Human missions

Technology Development at NASA

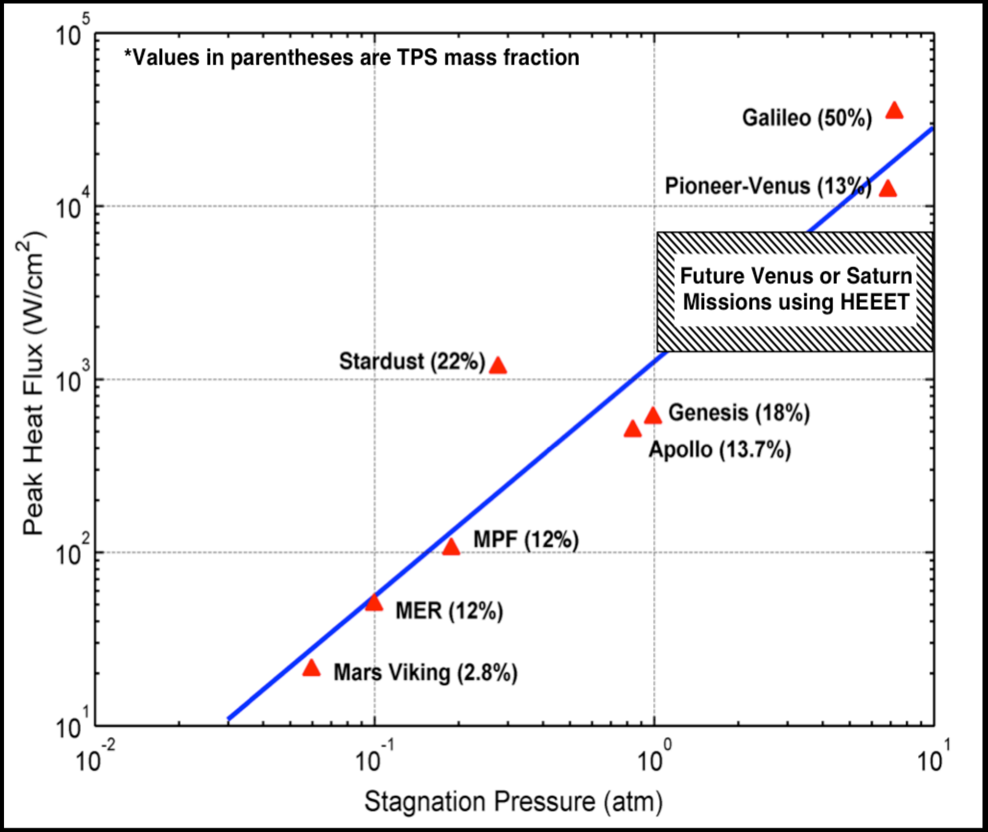
- Recognized that very little seed corn is left
- Bobby Braun was appointed as the NASA Chief Technologist (Feb., 2010)
- Space Technology Mission Directorate created (Feb., 2013).
  - Vision: "STMD rapidly develops, demonstrates, and infuses revolutionary, high-payoff technologies."
  - "By investing 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

NASA Future Missions and SOA in Entry and Ablative Thermal Protection Systems (2010)

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

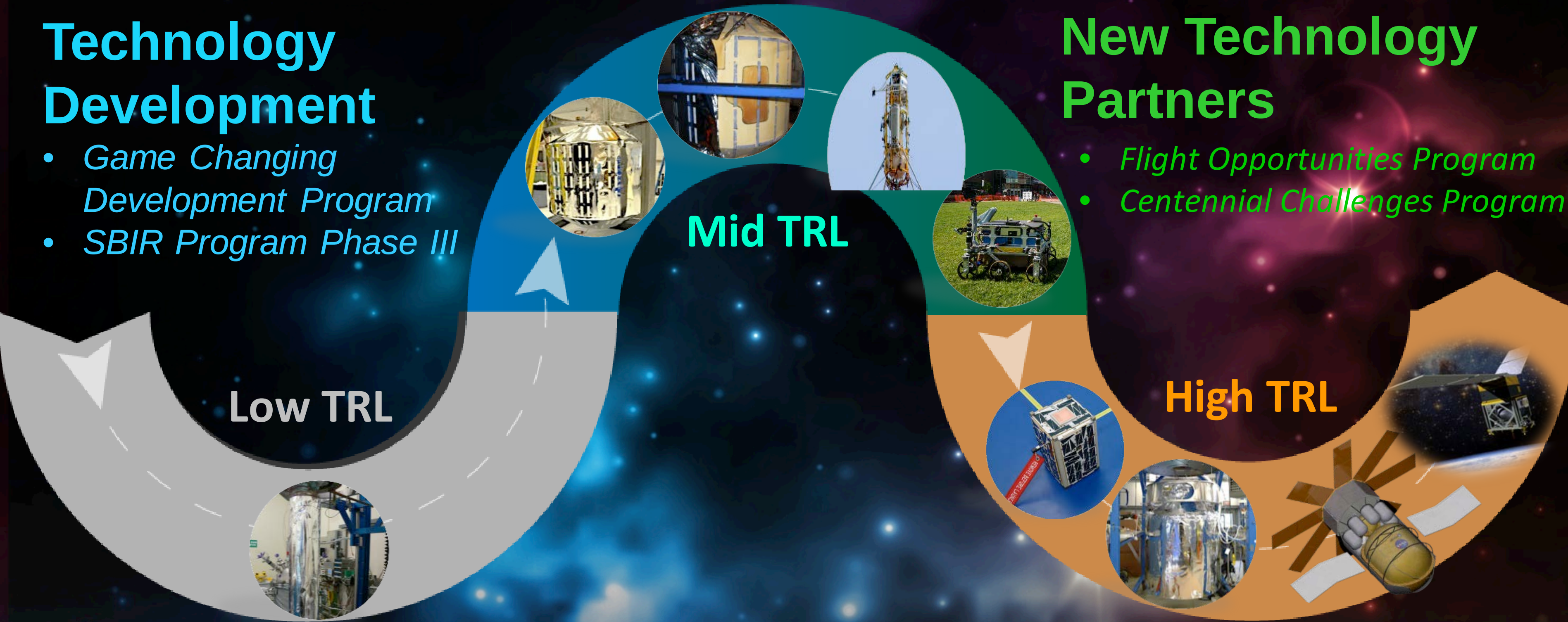


NRC recommended investment in key technologies
(e.g.: ablative TPS, conformal TPS, Deployable Entry System)

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*

Technology Demonstrations
- *Technology Demonstration Systems*
- *Small Spacecraft Technologies*

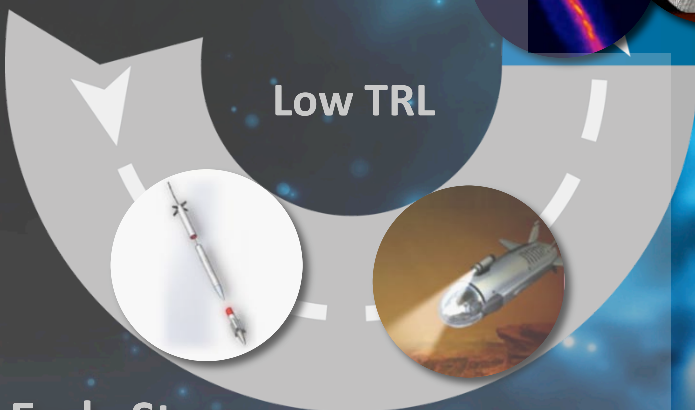
TECHNOLOGY PIPELINE

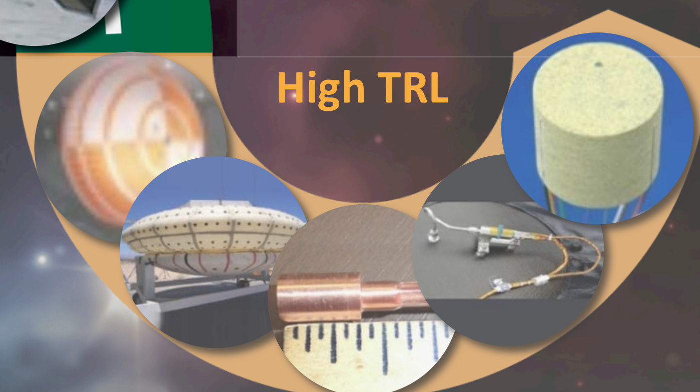
EDL Technology Pipeline
Game Changing Technologies

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

New Technology Partners
- *Flight Opportunities Program*
- *Centennial Challenges Program*

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





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

Technology Demonstrations
- *Technology Demonstration Systems*
- *Small Spacecraft Technologies*

TECHNOLOGY PIPELINE

9

Considerations for Game-Changing Development Funding
Game Changing Development Program View (May 2015)

Appropriateness	Is this a broad technology and not engineering/research?
Relevance/Alignment	Is the technology aligned with Technology Roadmaps, Decadal Surveys, etc.?
Value Proposition	What is the ratio of the potential benefits of the technology to the cost to mature the technology?
Leveraging/Partnering	Is the stakeholder/partner contributing resources?
Customer Advocacy	Do potential end users recognize the benefit and support the activity?
Development Plan & Infusion Potential	Is the activity well-planned, with appropriate schedule, budget, advancement milestones, KPP's, and options?
Acquisition Strategy	Is the proposed acquisition strategy the most effective strategy to mature the technology?
Timeliness	Is it critically important that this investment be initiated right now?
Maturity	As a general guideline, GCD initiates investments at a TRL = 3 and matures the technology to TRL = 5.

Conformal Ablative TPS Technology

Conformal Ablator TPS Development

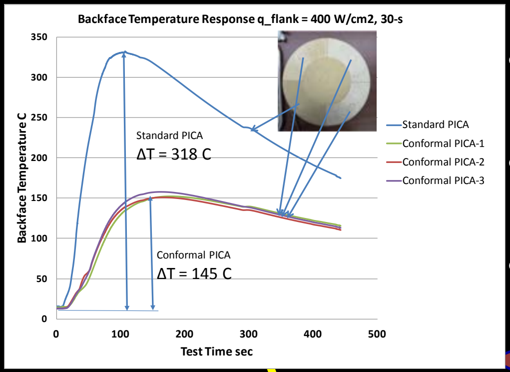
Conformal 1 Est.
Hyp EDL - FAP

2009 - 2011
Better
PICA / SIRCA

IHF 227
1000 W/cm^2
0.85atm

CA250 CPICA Improved,
Scale Up & Seam Design

2012
Mars 2020

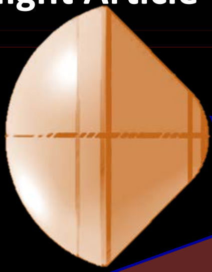


2013
ADEPT
Orion
Back-shell

ESM Advanced Conformal Ablators

2014
TVA
Small Probe

Flight Article



- Recession of CPICA = ~PICA
- Back face temp CPICA = ~1/2 PICA
- Compliance and Robustness
- CPICA >> PICA

2015
New Frontier
Orion EM3

IHF 289 1850 W/cm^2
1.5 atm, 10 sec
(CPICA and ACPICA)

Recession of
CPICA2 < PICA

3-D Woven TPS Technologies

3-D MAT, HEEET and ADEPT make use of advances made in the last decade in the Textile Industry.

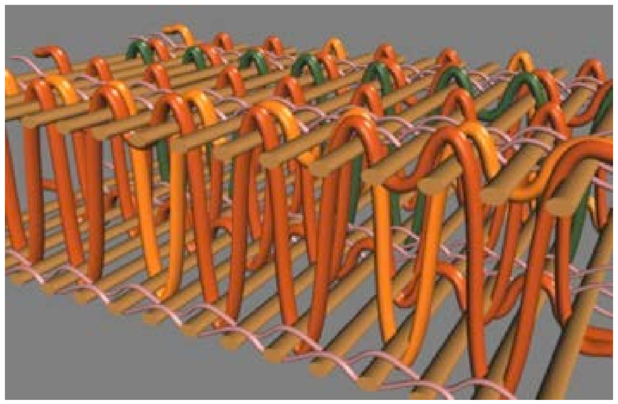
3D Weaving – A Quick Primer

2-D weaving (Fabrics that we wear).

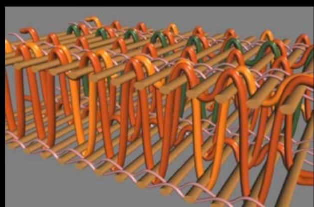
- Composites stack 2-D woven plies to make a laminate

3-D weaving

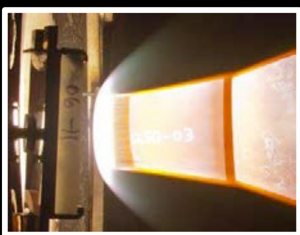
- Adds a yarn in the Z direction
- Architectures:
  - layer-to-layer, 3-D orthogonal
- Advances in textile engineering allow different compositions & densities to be combined in a single woven preform
- Preforms can be:
  - Non-resin infused (flexible) (ADEPT Fabric)
  - Resin infused (rigid) (3-D MAT & HEEET)



Exploring the Potential in 3-D Woven TPS Technology
(Center Investment Funds and Broad Area Announcement)



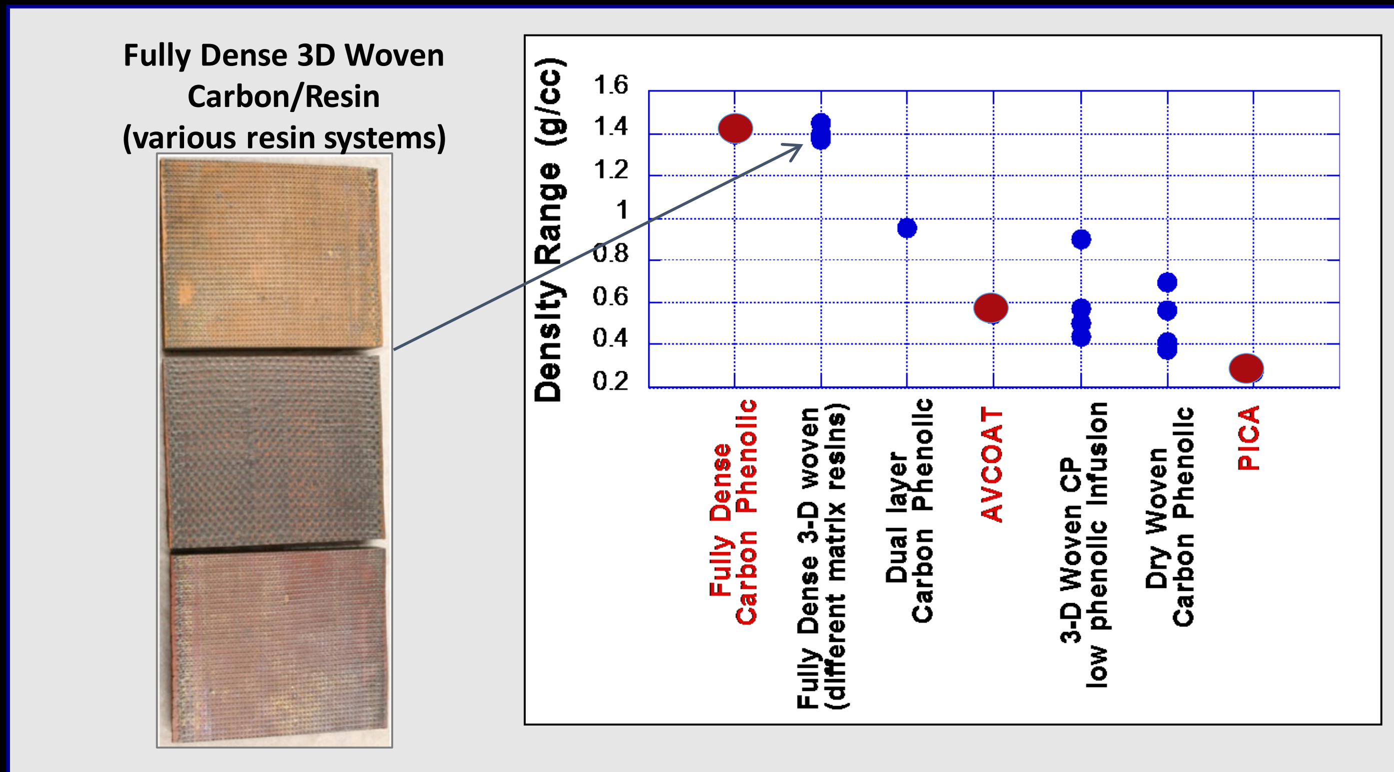
Woven TPS IR&D



Woven TPS GCT BAA

March 2011

Jan. 2012

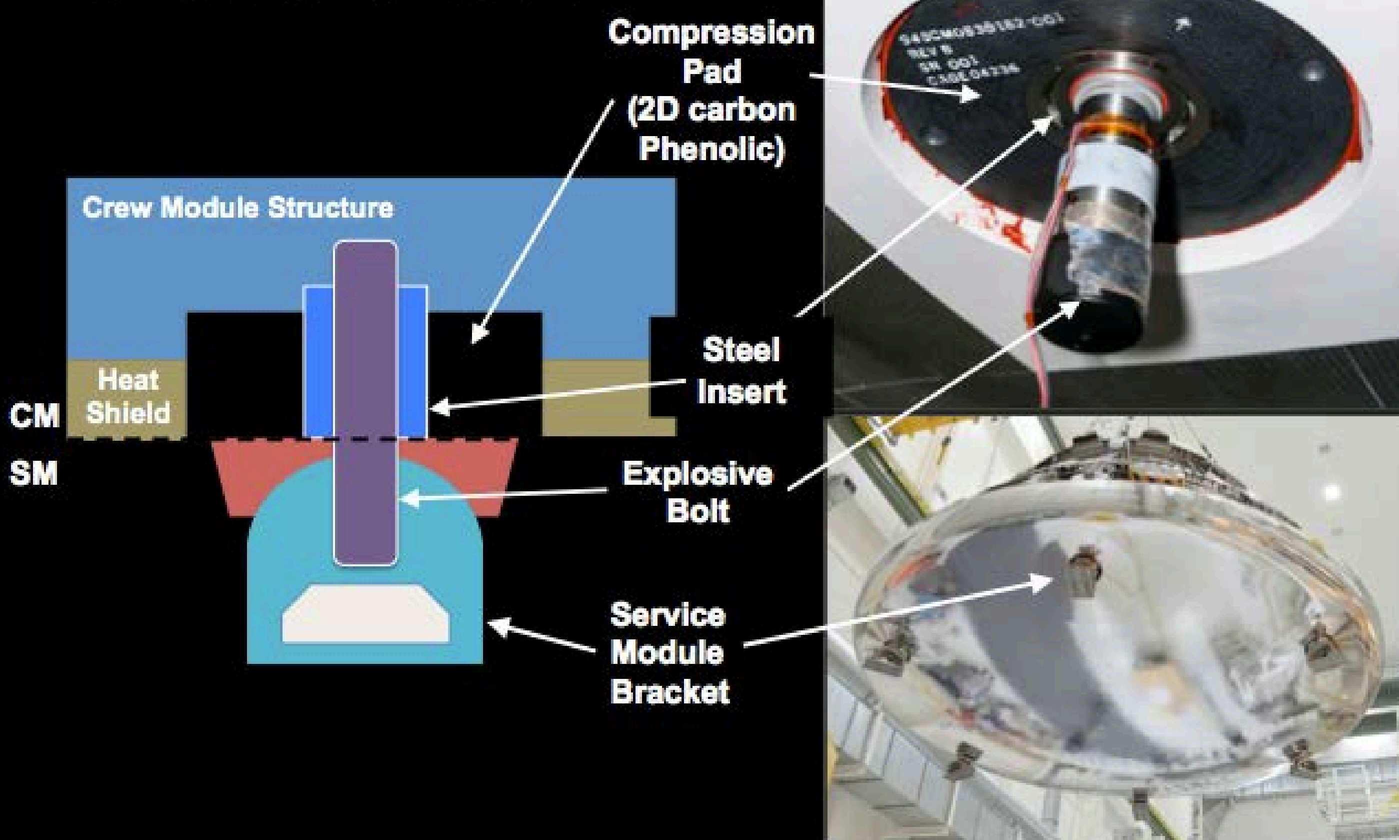


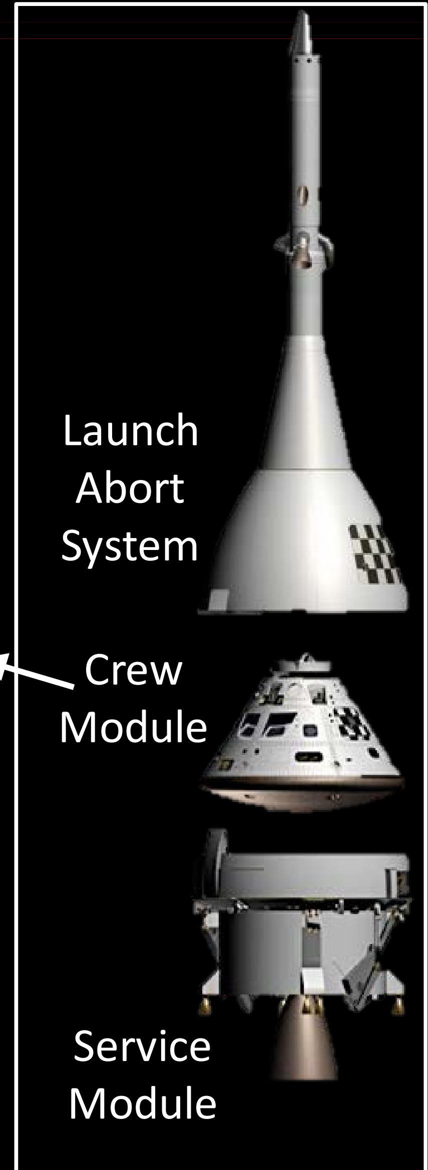
- **Woven TPS** is a family ablative materials
  - **3D-MAT (highest density) and HEEET (mid-density) applications are a product** of the Woven TPS family
- Lower density options
  - Mass efficient and robust option for Human Mars return missions

3-D Multi-functional Ablative TPS (3-D MAT) Technology

Orion Compression Pad Problem & Solution

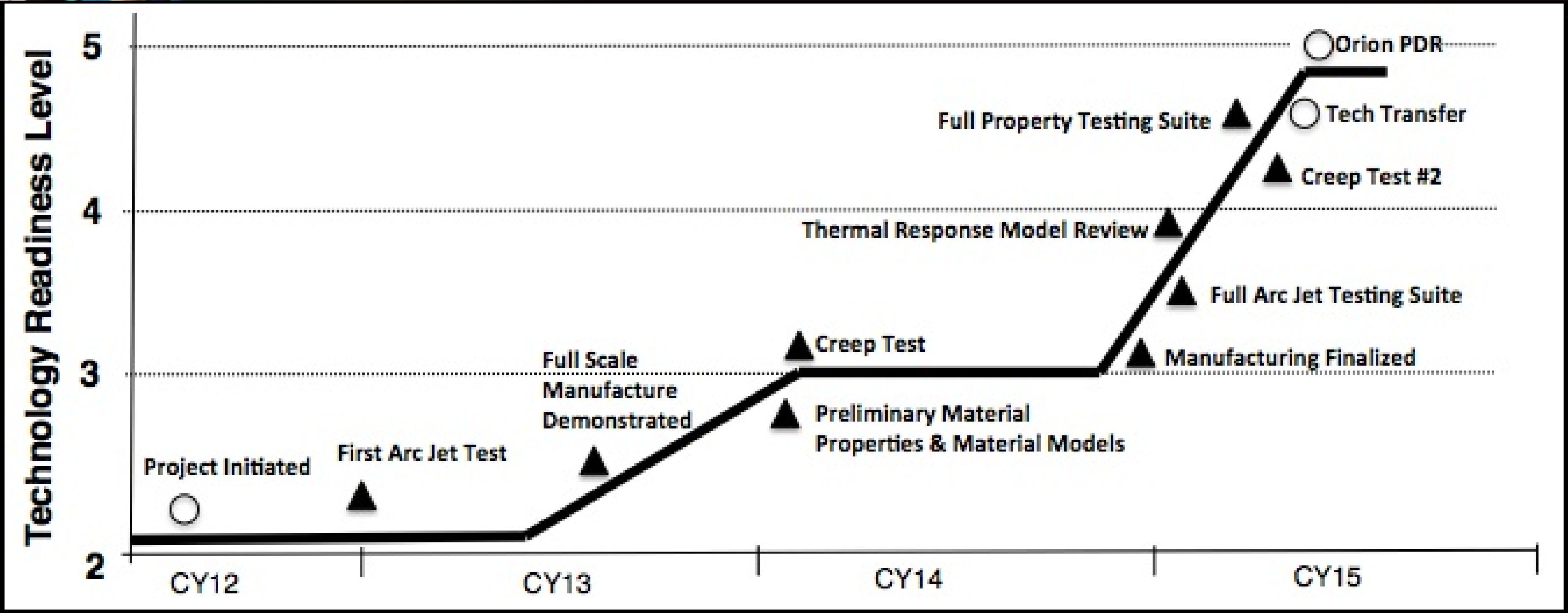
Compression Pad Mechanism





- 2D laminate and metalic 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.

3D-MAT Development Status



- 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 | **FY'14** | **FY'15** | **FY'16** | **FY'17**

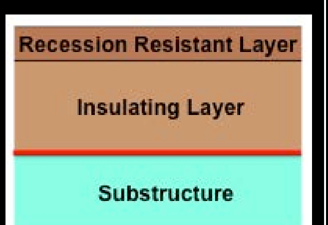
Formulation

TRL (3 – 6) Technology Maturation

FY'13

- Blended Yarn
- Resin Infusion
- Arc Jet Test
- Architecture Finalization

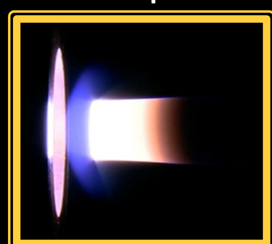
Yarn/Resin



2-Layer Architec.

FY'14

- Requirements
- Acreage Performance
- Material Prop
- Mold/Resin Development



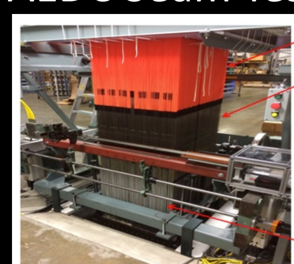
IHF-5000 W/cm2

LHEML 8000 W/cm2

FY'15

- Thermal Resp.
- Mold/Resin Scale-up
- Seam Selection
- Weave (12" x 2.1")

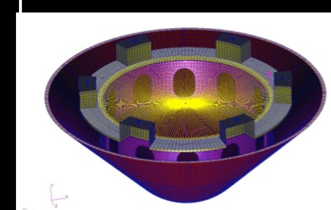
AEDC Seam Test



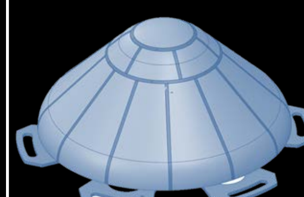
Loom Upgrade

FY'16

- MDU Build Complete
- Seam LHEML Verification
- Integration



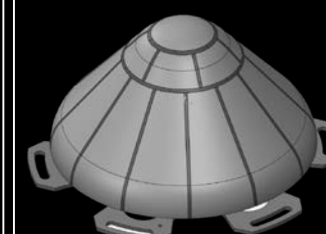
Carrier Structure



Manufacturing Develop. Unit

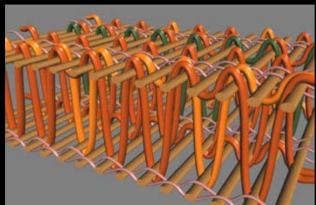
FY'17

- ETU Build Complete
- Valid. Arc Jet Testing
- ETU Testing completed
- Final Report and Docu.

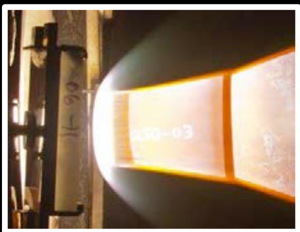


Engineering Test Unit (ETU)

3-D MAT and HEEET Development Background



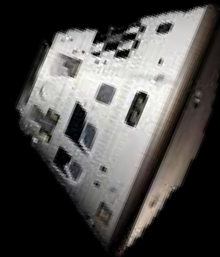
Woven TPS IR&D



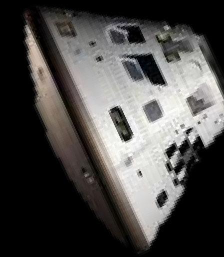
Woven TPS GCT BAA

3D Woven Multifunctional Ablative TPS (3D-MAT)

Enabling Orion with Lunar Capable Compression Pad



2018: Lunar



2022+: Crew

2020 – 2024

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

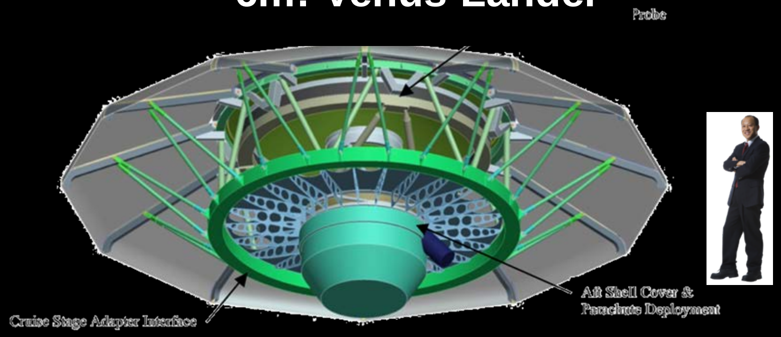
Robust Heat-shield for Human Missions (Future Potential)

Adaptable, Deployable Entry and Placement Technology (ADEPT)

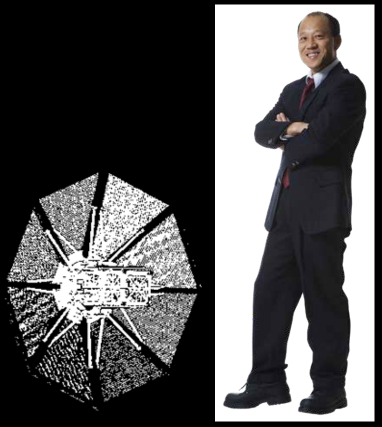
ADEPT Background

- 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

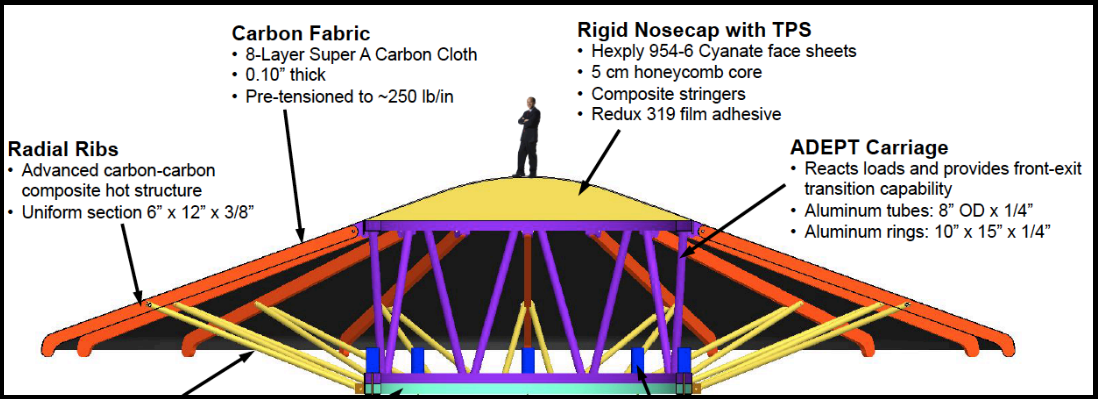
6m: Venus Lander



1m: "Nano" ADEPT



23m: Mars Exploration



ADEPT Development Highlights (FY12-mid FY15)

Carbon Fabric Combined Environment Performance (FY12)

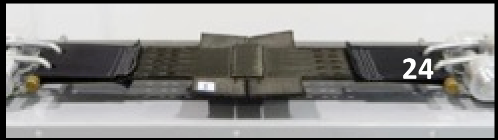
- Carbon fabric thermal and mechanical performance under relevant testing in arcjets.

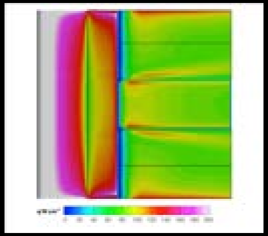
2 m Ground Test Article (FY13)

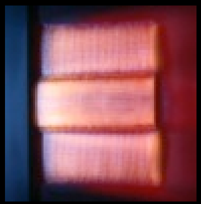
- Fabric gore manufacturing & integration process at 2 m scale
- Demonstrated reliable operational functionality of the mechanical design, software control logic, and system level integration

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

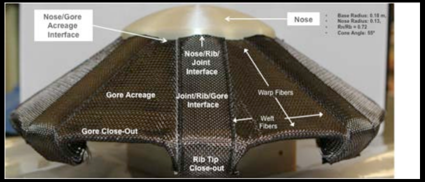




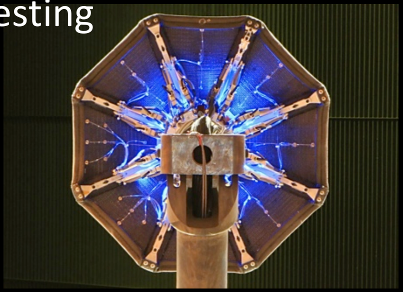


1m class System Testing (FY15)

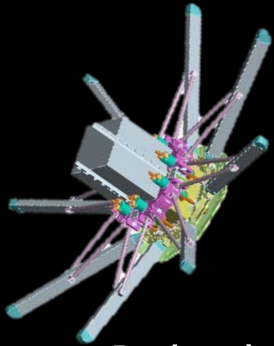
- SPRITE-C Arcjet testing



- 7x10 Wind Tunnel aeroloads testing

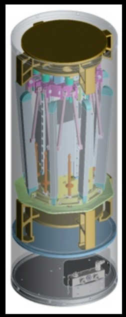


- Sounding Rocket flight test design and maturation



Deployed (shown w/o Fabric)

Stowed



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.

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

- 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 perceptional:

- 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 (perceptional)
- 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

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

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 Inter-dependent Review Board that includes mission infusers and stakeholders
  - Be transparent and develop trust with the user and stakeholder

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

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

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

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

Partnership	At initiation	Current	Comment
Conformal	None	Moderate	TVA as a partner brings flight data but it is not the same as mission infusion as originally envisioned. NF proposers – evaluating Conformal
3-D MAT	High	High	Orion and SBIR - funding partners. Vendor relationship excellent.
HEEET	High	High	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.
ADEPT	High	Low	Early focus on Venus – excellent partnership and advocacy. Partnership for Nano-ADEPT needs to be identified and worked

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

Competitive Assessment	Uniqueness at initiation	Current uniqueness	Comment
Conformal	Moderate (Alternate to PICA)	High value	Preliminary testing shows capable of ~2 kW/cm2 and 1.5 atm. Potential for Orion at V > 11.5 km/s with better mass savings
3-D MAT	Very high	Very High	Neither engineering redesign and other options did not pan out
HEEET	High	High	No alternate at this time with the robust and performance to meet extreme entry
ADEPT	High	High	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

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 ?

Concluding Remarks

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!