Planetary Exploration Science Technology (PESTO)

Venus Technologies

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Briefing to the Venus Exploration and Analaysis Group (VEXAG)
November 14, 2017
Laurel, MD

Visions and Voyages

"The committee unequivocally recommends that a substantial program of planetary exploration technology development should be reconstituted and carefully protected against all incursions that would deplete its resources. This program should be consistently funded at approximately 6 to 8 percent of the total NASA Planetary Science Division budget."

"The committee recommends that the Planetary Science Division's technology program should accept the responsibility, and assign the required funds, to continue the development of **the most important technology items** through TRL 6."

How to determine “the most important technology items”?

- Planetary Technology Working Group Members surveyed the VEXAG, OPAG, SBAG, Mars Program, and the Decadal Survey

- Then assessed each technology identified by the AGs using the following Figures of Merit:
  - Critical Technology for Future Mission(s) of Interest
  - Degree of Applicability across PSD Missions/needs
  - Work Required to Complete
  - Opportunity for Cost Sharing
  - Likelihood of Successful Development and Infusion
  - Commercial Sustainability

- Corporate knowledge includes previous studies, e.g.:

  “PSD Relevant Technologies,” G. Johnston 1/7/11

  https://solarsystem.nasa.gov/missions/techreports

🟩	TRL 6 and above
🟨	High TRL - limited development and testing needed
🟧	Moderate TRL - major R&D needed
🟥	Low TRL - notable technical challenges

Outer Planets input based on the OPAG white paper “Outer Planet “Roadmap of 2009

Community Technology Inputs

(VEXAG, OPAG, SBAG, Mars Program, Decadal, Surveys)

from: Planetary Science Technology Plan, April 9, 2015

		This decadal					Next decadal					After that				
		NEAR TERM MISSIONS					MID TERM MISSIONS					FAR TERM MISSIONS				
	Applicable Technology	Small Bodies	Outer Planets	Venus	Mars	Moon	Small Bodies	Outer Planets	Venus	Mars	Moon	Small Bodies	Outer Planets	Venus	Mars	Moon
SYSTEM TECHNOLOGIES	In Space Propulsion	🟨	🟩	🟩	🟩	🟩	🟧	🟧		🟩		🟧	🟧		🟧	
	Aerocapture/Aeroassist			🟩				🟨					🟧	🟨	🟧	
	Entry (including at Earth)		🟨	🟨		🟩		🟨	🟨						🟨	
	Descent and Deployment	🟩		🟩		🟩		🟧	🟧	🟨	🟩	🟧	🟧		🟥	
	Landing at target object			🟨	🟨	🟩	🟨	🟧	🟧	🟩	🟩	🟧	🟧		🟥	
	Aerial Platforms			🟨	🟨			🟨	🟨					🟧	🟥	
	Landers - Short Duration					🟩									🟧	
	Landers - Long Duration										🟨			🟧		
	Mobile platform - surface, near surface				🟨	🟨										
	Ascent Vehicle					🟩				🟧				🟥		
	Sample Return									🟧				🟥		
	Planetary Protection		🟨		🟨	🟨				🟧			🟧			
SUBSYSTEM TECHNOLOGIES	Energy Storage - Batteries	🟨		🟩		🟩	🟧	🟧	🟧	🟩	🟨	🟧	🟧			
	Power Generation - Solar	🟨					🟧				🟩	🟧	🟧			
	Power Generation - RPS							🟧	🟧		🟨 ?	🟧	🟧	🟥	🟨	
	Thermal Control - Passive		🟩	🟨		🟩		🟧	🟧		🟨	🟧	🟧	🟥	🟨	
	Thermal Control - Active															
	Rad Hard Electronics		🟩				🟩	🟧	🟩	🟩						
	Extreme Temp Mechanisms	🟨		🟨			🟧	🟧	🟧	🟩	🟨	🟧	🟧	🟧	🟨	
	Extreme Temp Electronics			🟩			🟧	🟧	🟧	🟩		🟧	🟧	🟧	🟨	
	Communications		🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟩			🟧		
	Autonomous Operations	🟨				🟩						🟧	🟧	🟧		
	GN&C	🟨			🟨	🟩	🟨	🟨				🟧	🟧	🟧		
INSTRUMENT	Remote Sensing - Active		🟨	🟩					🟨			🟧	🟨			
	Remote Sensing - Passive	🟩	🟨	🟩			🟨	🟨	🟨			🟧	🟨			
	Probe - Aerial Platform			🟨	🟨	🟨		🟨	🟨					🟨		
	In Situ - Space Physics											🟨				
	In Situ Surface - Geophysical						🟧	🟧	🟧					🟧	🟧	
	Sampling			🟨	🟩	🟨	🟧	🟧	🟧	🟩		🟧			🟨	
	In Situ Surface - Long Duration - Mobile				🟨			🟧						🟥	🟧	

Planetary Science Division Prioritized Technologies

April 2016

PLANETARY TECHNOLOGIES

- Electronics (high temperature)
- Communications (high bandwidth, high datarate)
- Solar Power (low intensity, low temp)
- Power Systems (high temperature)
- RPS surface power
- RPS orbital power
- System autonomy (GNC, Prox Ops, C&DH, sampling ops, FDIR)
- Small Spacecraft Power, GNC, Propulsion, Comm
- Planetary Ascent Vehicle for Sample Return
- Heat Shield technologies for planetary entry and sample return
- Computing and FPGAs (high performance/low power/rad hard)

INSTRUMENTS

- Life Detection for Ocean Worlds
- Low mass, low power instruments for cold, high rad ocean world environments
- Low mass, low power instruments for small spacecraft

OCEAN WORLDS

- Electronics (low temp, low power, rad-hard)
- Actuators/mechanisms (low temp)
- Planetary Protection Techniques/component and material compatibility
- Ice Acquisition and Handling (>0.2 m depth)
- Ice Sample Return
- Pinpoint Landing on Titan

EUROPA

- Ice Acquisition and Handling (surface, cryo)
- Batteries (low temp)
- Pinpoint Landing on Europa
- Landing Hazard Avoidance

Planetary Missions

Prioritized Technologies

- **High-Temperature Compatible Electronics**
- **High Bandwidth, High Data Rate Communications**
  - Large Deployable Reflectors and High Power TWTs
- **Low Intensity/Low Temperature Solar Power**
- **High-Temperature Compatible Power Systems**
  - Batteries
  - Power Generation
  - Low-Intensity High-Temperature Solar Cells
- **RPS Power**
  - Orbital and Surface: Radioisotope Thermoelectric Generator – eMMRTG
  - Orbital: Radioisotope Thermoelectric Generator - Next Gen RTG
  - Orbital and Surface: Dynamic RPS
- **System Autonomy**
  - Autonomous Navigation for EDL
  - Reactive Science Autonomy
  - Efficient Planetary Surface Science Ops
- **Small Spacecraft**
  - Propulsion – Electric & Non-Toxic Chem
  - Power, GNC,& Communications
- **Planetary Ascent Vehicle for Sample Return - Mars Ascent Vehicle**
- **Heat Shield Technologies for Planetary Entry and Sample Return**
  - Thermal Protection Systems
  - Aerocapture
  - Deployable Aeroshells
- **High performance/low power/rad hard computing and FPGAs**
  - Chiplet Augmentation, Advanced Space Memory, Co-Processors/Accelerators, System Software, Development Environment, Power, Computer

Prioritized Technologies - VENUS

11/2/17

DRAFT NEAR TERM

- **High-Temperature Compatible Electronics**
    - High-Temperature Communications
    - High-temperature Computing
- **High-Temperature Compatible Power Systems**
    - Batteries
    - Low-Intensity High-Temperature Solar Cells
- **Heat Shield Technologies for Planetary Entry and Sample Return**
- **Small Spacecraft**
    - Propulsion – Electric & Non-Toxic Chem
    - Power & Communications
    - Thermal Protection Systems
    - Aerocapture
    - Deployable Aeroshells

DRAFT MID TERM

- **High-temperature Power Generation Systems**
- **System Autonomy**
    - Autonomous Navigation for EDL
- **GNC**
    - Attitude Determination and Control (ADC)

DRAFT FAR TERM

- **High performance/low power/rad hard computing and FPGAs**
- **High Bandwidth, High Data Rate Communications**
    - Large Deployable Reflectors and High Power TWTs
- **Planetary Ascent Vehicle for Sample Return**

Existing RPS program

- **RPS Power**
    - Orbital and Surface: Radioisotope Thermoelectric Generator – eMMRTG
    - Orbital: Radioisotope Thermoelectric Generator - Next Gen RTG
    - Orbital and Surface: Dynamic RPS

- NEW **Deployable mechanisms**
    - aerial platforms, long duration landers
- NEW **Sample Acquisition and Transport for high temperature/harsh atmosphere**
    - Electric motor, arm, actuator
- NEW **Active cooling**
- NEW **Atmospheric Sample Return**

Prioritized Technology: High Temperature Electronics

Technical Goal

- The goal is operation of high temperature electronics for extended periods (months or years), without cooling, with functionality that is as capable as that for other planetary environments despite the harsh conditions.
- Operational environments include:
  - Venus surface environments at temperatures of ≥470°C in high pressure for long duration missions (>3000 hours).
  - Mercury surface missions with surface temperature near a maximum of 430°C, with significant temperature variations.

- Operation in other planetary application environments, such as probes into Gas Giants where the temperature and pressure increase as probes descend into the atmosphere, but also resilience to high radiation (rad-hard).

Mission Applications

- Examples for Venus exploration include:
  - A long-lived surface science station based on simple operational principles (Near Term)
  - A networked seismic network coordinated in multiple locations across the planet. (Near-Mid Term)
  - A long-lived lander with selected instrumentation based on high temperature electronics performing surface and sample investigations at a given location. (Mid Term)
  - A mobile rover with selected instrumentation performing surface and sample investigations at multiple locations. (Mid-Far Term)
- Similar investigations could be envisioned for Mercury.
- Probes into the atmosphere Gas Giants at greater depths, with associated temperatures and pressures.

Technical Status

- Limitations in the temperature range and durability of conventional electronics to e.g., less than 2 hours demonstrated Venus surface operation, combined with a lack of radiation hardness, effect all aspects of science mission operations in harsh environments .
- High temperature SiC electronic circuits have operated at Venus relevant temperatures for sustained periods
  - SiC electronics demonstrated world-record ability for simple and selected moderately complex circuits with packaging to operate for thousands of hours at 500°C in air ambients.
  - Operation of specific moderately complex circuits for extended periods in-situ in Venus surface atmospheric conditions has been demonstrated for more than 500 hours.
  - Circuit operation up to 700˚C for briefer periods of time has been demonstrated; relevant to, e.g., deep atmosphere probes.
  - Other circuits can be designed and fabricated based on this core technology
- Work has begun on a Venus lander science station with electronics for sensor control and signal processing, power supply management, and communications with a targeted operational lifetime of at least 60 days.
- Other high temperature electronics approaches are in development, but at a less mature stage.

Prioritized Technology: High-Temperature Compatible Power Systems
Batteries

Capability Description

Batteries for high temperature applications such as Venus surface missions

1. High temperature capability up to 500 °C
2. Extended mission capability 3000 hrs or more, providing 50 – 100 W peak power
3. Capable of handling high pressure (90 bar) corrosive environment.
4. For early Venus surface missions, battery will need to operate for a few minutes at a time and provide 7 to 10 Watts of power.

Capability Status

- Molten salt thermal batteries heated to 400 – 550 °C are used in missile applications for short durations.
- A prototype thermal battery designed for the MSL Descent Stage was flight qualified (fabricated by Eagle Picher)[1]. Operation design life was 30 minutes.
- Thermal batteries become an ambient temperature solution for Venus.

Mission Applications

- High temperature capable batteries will be enabling for any Venus surface mission with a duration of more than a few hours.
- A primary battery may be sufficient for a mission lasting one Venus solar day (3000 hours).
  - A rechargeable battery that can function as a primary battery would be usable for both near and far term missions.
  - This same battery is adaptable to Jupiter and Europa missions

Prioritized Technology: High-Temperature Compatible Power Systems
Low-Intensity High-Temperature Solar Cells

Capability Description

- Solar cells that can operate at temperatures above 450 C and 90 bar and can work with low intensity illumination.

- In addition, for destinations to the Venus surface the solar cells must be chemically resistant to harsh environments.

Capability Status

- Low Intensity High Temperature (LIHT)solar cells do not exist beyond the laboratory concepts.

- Current technologies have not been tested beyond 400 C.

- New technology using high bandgap semiconductors has some promise for reaching the goal of operation at 450 C.
  - The TRL for this technology for solar cells is currently TRL 1 or TRL 2 at best.

Mission Applications

- Venus surface power for mid-term and far term missions.
  - These types of missions will be longer duration and will require a power source to recharge the batteries.

- For applications higher in the atmosphere, the temperatures will be somewhat less extreme and more illumination will be available, but the harsh chemical environment will still be present.

- Existing solar technology might work on Venusian mountain tops.

Prioritized Technology: Small Satellites – Electric Propulsion

Technical Goal

(1) Long-duration thruster firings are required to generate high delta-V, therefore high Isp is needed to reduce the propellant mass and volume to fit within a SmallSat. Rad-tolerant to survive long-duration flight in deep space. Requires high power solar arrays.

  a. Packages to 3U-4U. 150-300 W (I_2 or Xe) (1300 – 1500 sec, 2,000 to 10,000 hours).

  b. ESPA-class. 300-600 W (Xe or I_2) (1300 – 1500 sec, 6,000 to 10,000 hours(.

(2) System packages to <1U. Rad-tolerant to survive long-duration flight in deep space. <100 W, 0.1 to 1.2 mN, 2000-5000 sec Isp, 5,000 to 15,000 hours. Typically BIT (Xe or I_2), or electrospray (ionic liquids).

Mission Applications

(1) Direct transportation to the moon, Mars, Venus, and main asteroid belt from GTO; higher power missions e.g. to Europa.

  a. CubeSat missions

  b. ESPA-class missions, enables larger science payload.

(2) Enables low power, rideshare missions <12U. Missions like LunaH-Map, Lunar IceCube, and DAVID. No new power system requirements.

Technical Status

The gap is lifetime.

1) 100 to 600 W electric thrusters performance has been demonstrated with the required Isp and thrust. Flight-like power processing units have not been developed (compact, high power density, rad hard). Iodine cathodes have not yet been developed.

  a. 200 W Xe thrusters have demonstrated 1800 hours of operation (then soft failure), and 80 hours using iodine propellant (test ended before failure). 200 W, 30 krad iSat flight PPU being built.

  b. 600 W I_2 thrusters have demonstrated 80 hours of operation (test ended before failure). 600 W brassboard PPU being built

(2) 100 microNewton thruster performance demonstrated to 200 hours until failure (MIT). In-space demo with limited operability (MIT 2015 and 2016, Busek 2018). BIT thruster 500 hour life test. MicroNewton thrusters flew on LISA Pathfinder.

Prioritized Technology: Heat Shield Technologies for Planetary Entry and Sample Return – Thermal Protection Systems

Technical Goal

Thermal Protection Systems (TPS) and integrated entry vehicle system technologies are required to accomplish missions at the most challenging destinations in the Solar System. TPS and entry vehicle technologies are also required for high-speed Earth return of samples from various Solar System bodies such as comets, asteroids, moons, and other planets.

1. Peak heating rates of ~ 5000 W/cm^2 & pressures in excess of 5 atmospheres
2. Entry system mass fractions less than 30-40% for trajectories limiting payload structural loads to 10-50 g's.
3. Reliable (<10^6 chance of failure) entry systems for biological sample return.

Technical Status

- **Earth Return**: **PICA.** Heritage PICA (Stardust, OSIRIS-REx, MSL, Mars2020) no longer sustainable due to discontinued rayon manufacturing.
    - Stardust (0.83 m monolithic PICA TPS; 12.6 km/s, 1200 W/cm^2 peak).
- **Venus**: Previous carbon phenolic (CP) heatshields (e.g. Galileo) had mass fractions in excess of 50% resulting in trajecotries subjecting the payloads > 300 of g's. CP is no longer supported by the supply chain.
    - Pioneer (0.76-1.42 m carbon phenolic; 11.5 km/s, 3900-5500 W/cm^2)
- EDL systems must be sufficiently instrumented to provide the data required to effectively model the Discovery and New Frontiers AO's. The Mars 2020 heatshield and backshell include engineering sensors to collect temperature, heat flux, radiation, and pressure data.

Mission Applications

- Technology maturation is enabling for Venus, Saturn, Uranus, Neptune, and Ocean World missions.
- Reduced entry system mass will reduce launch and qualification costs Venus, Saturn, Discovery, and New Frontiers missions.
- Highly robust Entry system technologies will enable the high-speed Earth return of potentially biologically-active samples.
- Improved validated modeling techniques will reduce design margins, better quantify risk, and certify entry systems for all NASA missions.

Prioritized Technology: Heat Shield Technologies for Planetary Entry and Sample Return – Deployable Aeroshells

Technical Goal

- There are several key challenge areas that must be addressed in advance of mission infusion (challenges vary with scale and environment).
  - Development and demonstration of flexible thermal protection system (TPS) materials at large scale.
  - Demonstration of thermostructural stability for high temperatures and high structural loads.
  - Management of load transfer and aeroshell shape stability/control with scale-up.
  - Reliability of deployable/inflatable Entry, Descent, and Landing (EDL) architectures.

Technical Status

- The state of the art is high ballistic coefficient aeroshells with metallic substructures and rigid thermal protection system (TPS) resulting in heavy systems constrained by the size of the launch vehicle shroud.
- Traditional aeroshell technologies are currently at the size limit for Mars payload mass capability (1 metric ton).
- Two successful hypersonic inflatable aerodynamic decelerator (HIAD) 3-m scale sounding rocket tests (latest in 2012). Six-meter ground article built and tested. Twelve-meter-scale inner toroids manufactured. Six-meter article test from Earth orbit planned for FY21.
- 0.7-m scale mechanical deployable (ADEPT) aerodynamic and arcjet testing completed. Sounding rocket test funded and scheduled for FY18.

Mission Applications

- Deployable aeroshells are applicable to both Aerocapture and EDL for Venus, Earth return, Mars, and Titan missions.
- Deployable aeroshells may enable secondary aerocapture or entry probe payloads for Discovery-class missions or Technology Demonstration Opportunities.
- Inflatable/deployable aeroshells offer several benefits as compared to traditional, rigid, fixed-shape aeroshells.
  - Reduced entry system mass fraction and improved payload packaging flexibility.
  - Low deceleration loads for the safe delivery of sensitive scientific instruments.
  - Can eliminate the need for supersonic parachutes at Mars
  - Higher-altitude deceleration increases planetary surface access and allows more time for precision landing sensor acquisition
  - Elimination of launch-shroud constraints on aeroshell diameter.
  - Flexible thermal control and communications during interplanetary cruise

Prioritized Technology: Heat Shield Technologies for Planetary Entry and Sample Return – Aerocapture

Technical Goal

- Aerocapture implementation challenges include:
  - TPS sizing/selection for some destinations,
  - sufficient knowledge of the atmospheric density profiles, and
  - algorithms for aerocapture guidance and control.

Mission Applications

- Aerocapture is applicable to Venus, Earth, Titan, Neptune, and Mars missions.
- Uranus application needs further study
- For planetary bodies with an atmosphere, using atmospheric drag to provide aerodynamic deceleration (aerocapture) results in significant mass savings as compared to propulsive orbit insertion methods.
- Aerocapture offers many advantages over aerobraking and the mission-enabling features associated with aerocapture may be essential for future SMD exploration missions.
  - Establishes science orbit immediately upon arrival, reducing risks of multi-pass aerobraking
  - Eliminates multi-month aerobraking operations costs, and complexities associated with long-distance operation

Technical Status

- Hypersonic guidance was achieved on the Mars Science Laboratory
- Systems definition studies have been conducted for aerocapture orbiters at Venus, Mars, Titan, and Neptune
- Analytical studies have demonstrated the feasibility of aerocapture and have identified potential savings in the propellant requirements (95%) and overall system mass.
  - Aeroshell mass fractions have improved since those early-2000’s studies
  - These analytical results have not been validated with flight data.
- Given the lack of flight heritage, cost-effective demonstration of aerocapture will accelerate adoption for the critical path on planetary missions:
  - Low-cost demonstration options have been identified, but the concepts must be analytically refined, matured, and ultimately implemented.
  - Small satellites and SLS secondary rides may be leveraged to perform affordable demonstrations.
  - In addition to demonstrating feasibility, critical data will be obtained and applied to future system designs.
- Neptune and Uranus aerocapture require control authority beyond that of blunt bodies (new shape), and have challenging TPS requirements