Technology requirements overview from the Assessment Groups (OPAG, MEPAG, VEXAG and SBAG) to the Decadal Survey Panels and Steering Committee

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Planetary Science Technology Review Panel

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TOPICS

(Science and) Technology Recommendations from:

- OPAG
- MEPAG
- VEXAG
- SBAG
- Summary
- Additional recommendation

Outer Planet Assessment Group (OPAG) Technology Priorities for Outer Planet Exploration

Topics covered

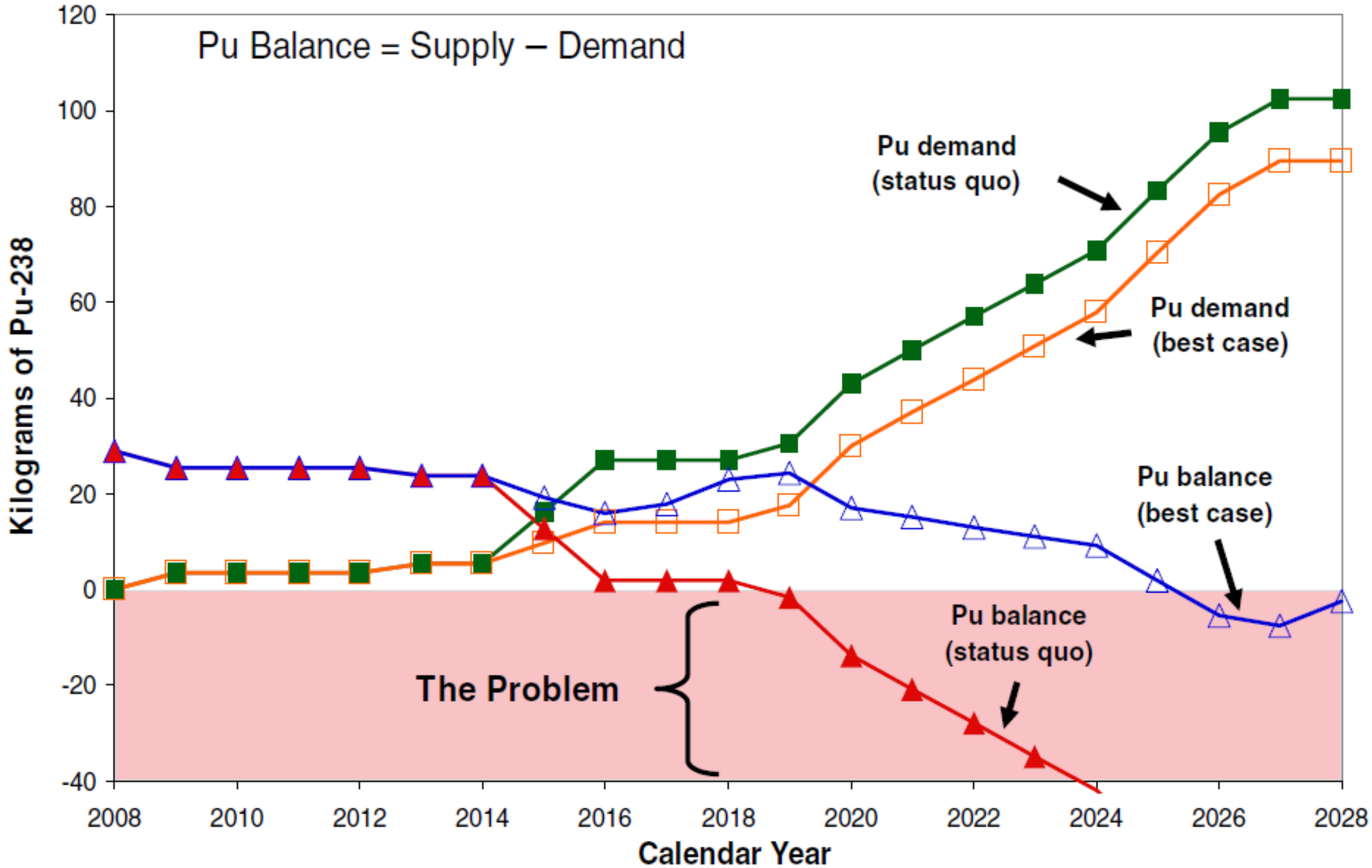
- Summary of OPAG Science Recommendations
- OPAG Top Seven Technology recommendations
- Priorities
- Summary
- Specific List of OPAG Recommendations

OPAG Science Recommendations

- **OPAG recommends that the Decadal Survey explore the possibilities for a program structure/categorization that could allow 'small flagship' class missions to be considered.**
- **OPAG strongly endorses the prioritization by NASA of the Jupiter Europa Orbiter (JEO) as the next Outer Planets Flagship and as part of the Europa Jupiter System Mission (EJSM) with ESA.**
- **OPAG strongly endorses approval by NASA of the Cassini Solstice Mission, including the Juno-like end-of-mission scenario.**
- **OPAG advocates the need for a focused technology program for the next Outer Planet Flagship Mission, which should be to Titan and Enceladus, in order to be ready for a launch in the mid-2020s.**
- **New Frontiers class missions that should be considered in the interim include (but *not in priority order)* a shallow Saturn probe, an Io observer, a Titan *in-situ* explorer or probe, a Neptune/Triton/KBO flyby and a Uranus Orbiter**
- **Support for underlying Research & Analysis, Laboratory Studies, and Earth-based observations should continue.**
- **Effective international involvement is strongly encouraged in the planning, development, and analysis phases of all space missions to the Outer Solar System, beginning at the earliest stage possible.**

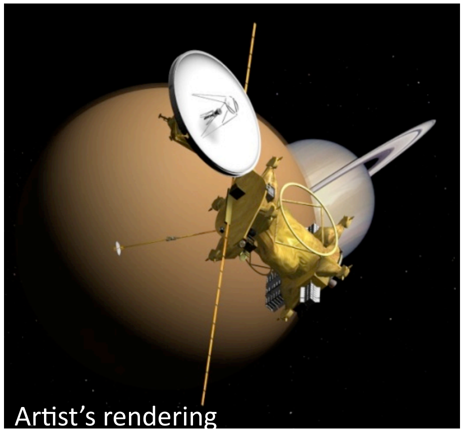
OPAG Top Seven Technology recommendations

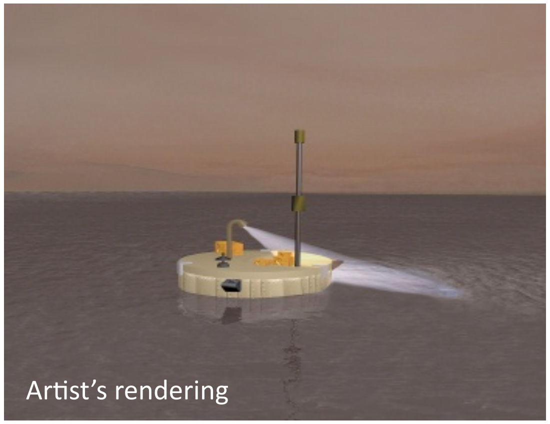
1. NASA should work with the relevant agencies to ensure that Pu-238 production (processing) is restarted and provides enough material for future outer planet missions. In particular, NASA should flight-qualify ASRG power systems.



(Hoover et al. 2009. *Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration. National Academies Press, ISBN 0-309-13858-2)*

OPAG Top Seven Technology recommendations





2. A focused technology program for the next Outer Planet (OP) Flagship mission should be initiated to ensure readiness for launch in the mid-2020s. Current planning indicates a mission to Titan/ Enceladus will be highest priority. NASA should fund:

- **risk reduction of the montgolfière balloon element**
- **autonomy capabilities to maximize science return of balloon element at Titan**
- **landing technologies required for sampling the high latitude lakes, dunes and cryovolcanic regions**
- **components for operation in the 90 K Titan environment**
- **in situ sample acquisition and sample handling in 90 K Titan environment. Also instruments (see #7).**

OPAG Top Seven Technology recommendations

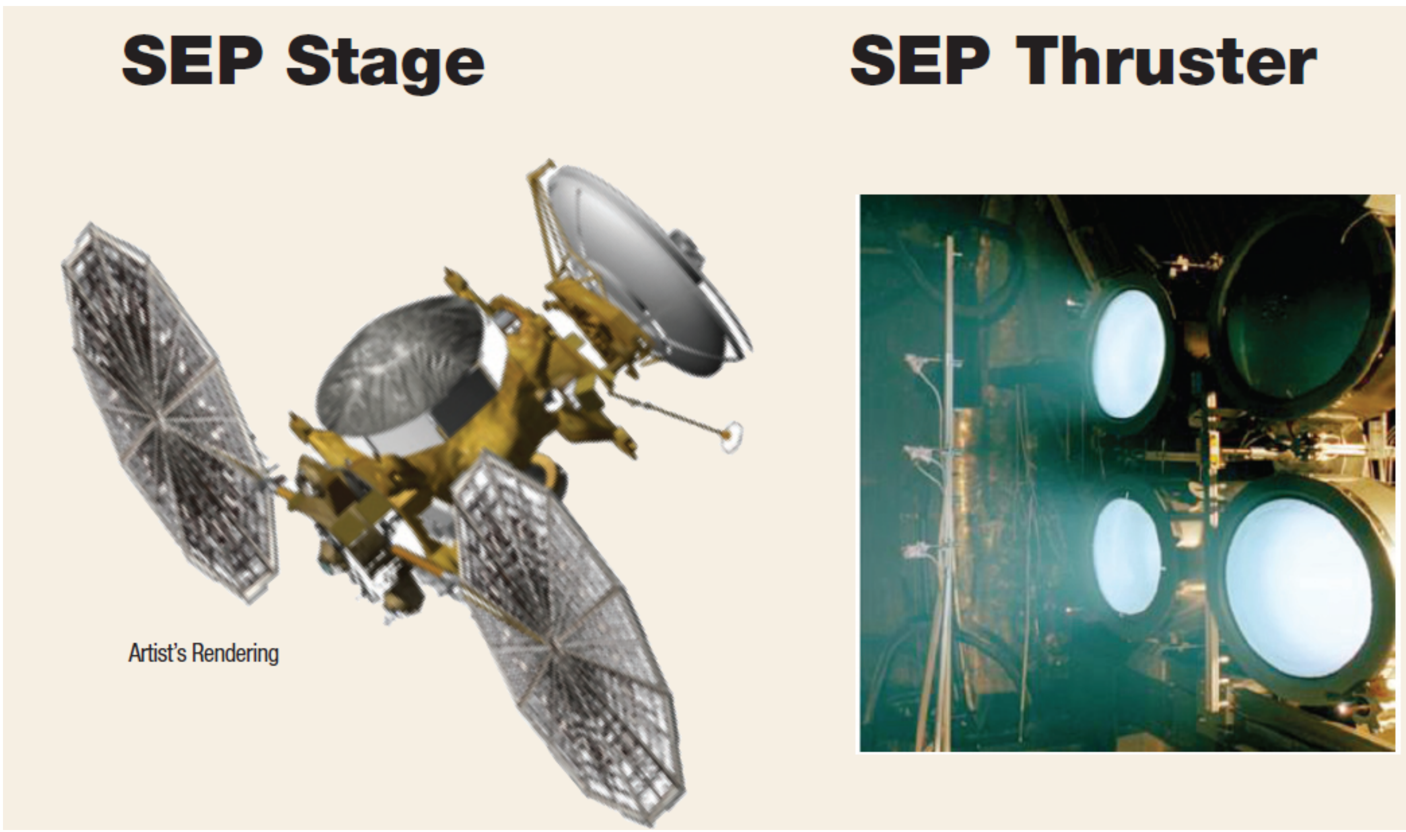
3. NASA should expand the funding of communication and radio science technologies required for the outer planets, especially making Ka band operational and furthering proximity and direct-to-Earth communication technologies. In addition, it should also sustain and accelerate DSN antenna arraying.

Meeting the Challenge of Outer Planets Telecom

- Ka-band (higher frequency)
- Larger ground and space antennas (and arrays)
- Higher power flight transmitters
- Next generation flight transponders
- Precision Radio Science integrated into Telecom
- Optical Communications

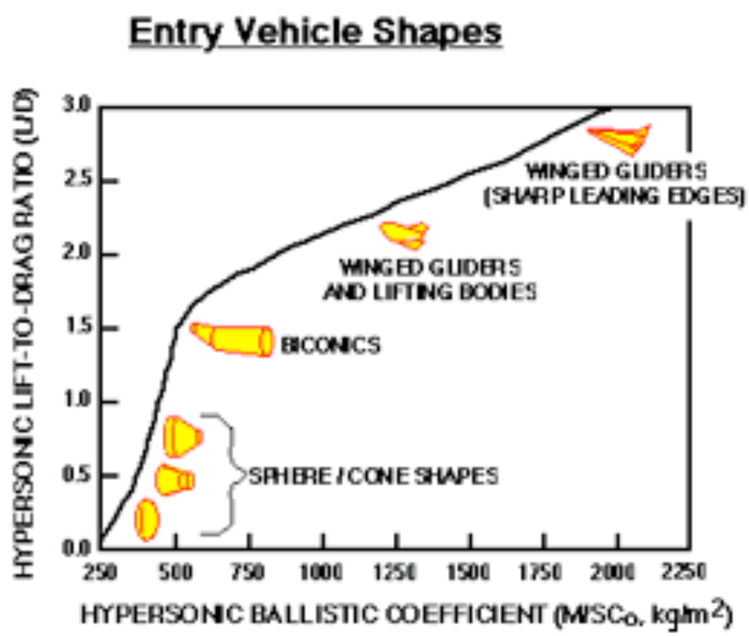
OPAG Top Seven Technology recommendations

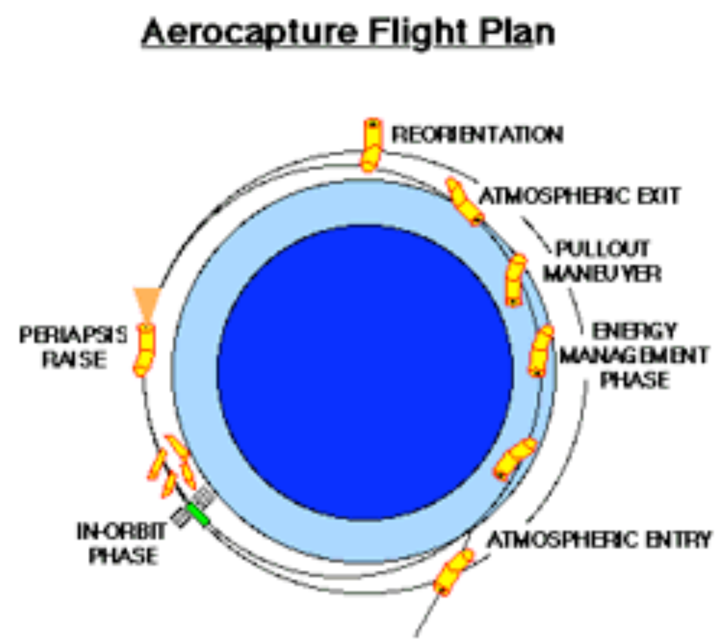
4. NASA should continue to invest in development of underlying technologies (thrusters, power and control, propulsion technologies) for solar electric propulsion, to bring these systems to flight readiness and to make the capability affordable to and within the risk postures of different mission classes.



OPAG Top Seven Technology recommendations

5. NASA should invest in aerocapture technologies and consider a space-flight validation of aerocapture in advance of the decision points of identified missions.





Ref: Advanced Space Propulsion Concepts, JPL Website.

OPAG Top Seven Technology recommendations

6. For planetary probes, OPAG recommends investment in the development of alternative thermal protection systems (TPS) materials, and periodic limited manufacturing and testing demonstrations to ensure heritage TPS manufacturing is kept current.

Table 1. Candidate ablative TPS materials for Outer Planet probe applications

Density	TPS	Supplier	Flight Qual or TRL	Potential Limit		Mission Set				
				Heat flux, W/cm²	Pressure, atm	Saturn Pro-grade	Saturn Retro-grade	Neptune Direct	Neptune Aerocapture	Jupiter High Latitude (Pro-grade)
FOREBODY HEAT SHIELD										
Low-Mid	PICA	FMI	Stardust	~ 1200	< 1	✖	✖	✖	✖	✖
	Avcoat	Textron	Apollo	~ 1000	~ 1	✖	✖	✖	✖	✖
Mid	ACC	LMA/ C-Cat	Genesis	> 2000	> 1	◡	✖	✖	✖	✖
	Mid-density carbon phenolic (0.8-1.0 g/cm³)	Several capable, none active	TRL 3	> 2000 < 5000	> 1	◡	✖	✖	✖	✖
	PhenCarb family	ARA	TRL 5-6	> 2000 < 5000	> 1	◡	✖	✖	✖	✖
High	3D Woven QP	Textron	DOD TRL 3	≥ 5000	> 1	◡	✖	✖	✖	✖
	Heritage Carbon Phenolic (TWCP & CMCP)	Several capable, none active	Venus, Jupiter	10,000-30,000	>> 1	●	●	●	●	✖

Ref: WHITE PAPER TO THE NRC DECADAL SURVEY OUTER PLANETS SUB-PANEL
Thermal Protection System Technologies for Enabling Future Outer Planet Missions *by* Ethiraj Venkatapathy* (Lead), James Arnold**,Bernard Laub*, Helen H. Hwang*,Christine E. Szalai***, Joseph L. Conley* and 90 Co-authors

OPAG Top Seven Technology recommendations

7. NASA should achieve a better balance between component development, in situ and remote sensing (active and passive) instrument definition, and instrument development, with a focus on demonstrating complete instrument systems and bridging the gap to flight. An OP instrument program should focus on developing and maturing low mass/power instrument systems that have high resolution and sensitivity, raising the TRL to >6.

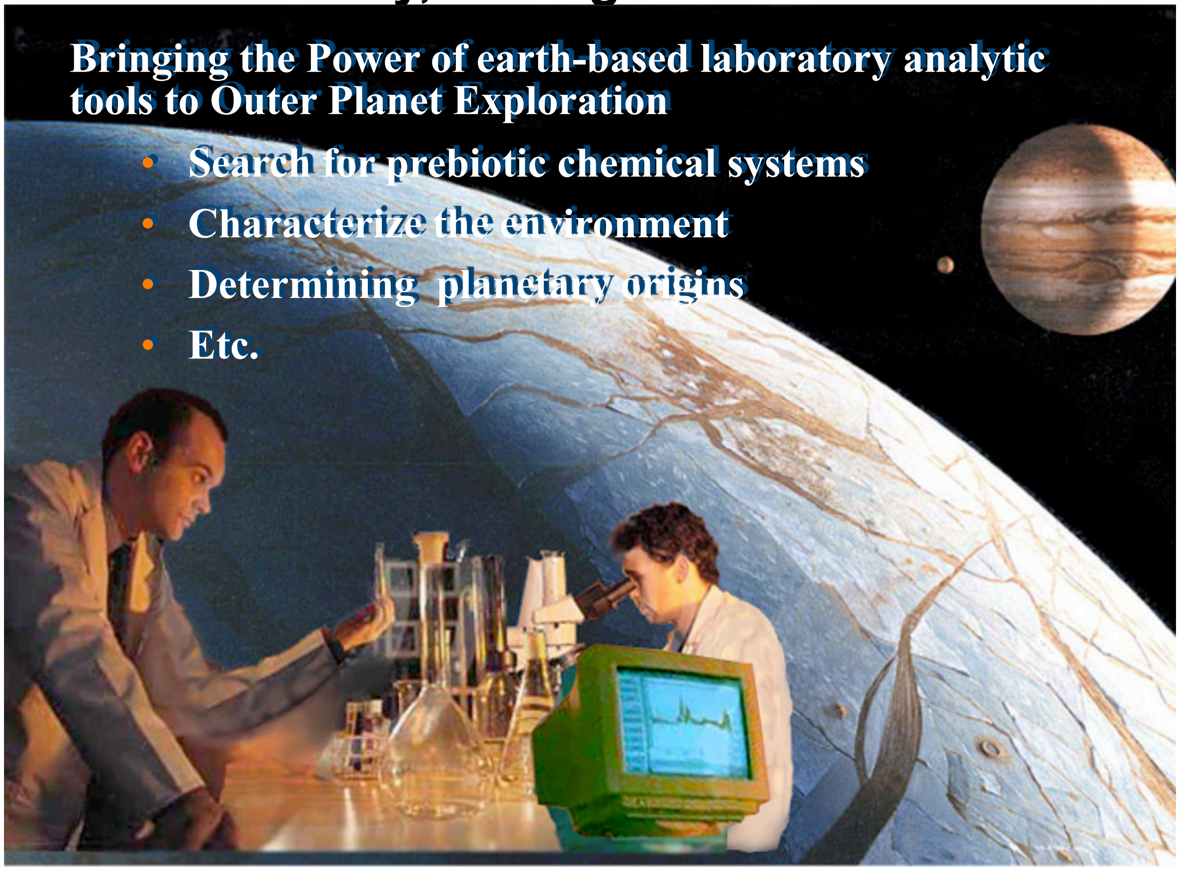


Table 2. Summary of Technologies required for Outer Planet Missions

Technology Development	Missions								
	Titan Orbiter *In Situ* Sampler	Neptune Orbiter	Neptune Flyby to KBO Flyby	Uranus Orbiter	Saturn Probe	Jupiter Probe	Neptune Probe	Enceladus Sample Return	Europa Lander
Power									
RPS	**E**	**E**	**E**	**E**	**e**	**e**	***E**	**E**	**e**
Low intensity, low temperature solar arrays				**e**	**e**	**e**			
Transportation									
Electric propulsion	**e**	**E**	**e**	**e**	**e**		**e**	**e**	
Aerocapture		**E**		**E**					
Communications									
Expanded Ka capability	**e**	**e**	**e**	**e**			**e**		**e**
Improved proximity links	**e**				**e**	**e**	**e**	**e**	**e**
Improved UHF systems	**e**				**E**	**e**	**E**	**e**	**e**
Planetary protection measures	**e**							**e**	**e**
Mobility and Landers	**E**								**e**
Autonomy	**e**							**E**	**E**
Extreme environments	**e**				**e**	**e**	**e**	**e**	**E**
Entry systems (includes TPS)	**e**	**E**		**e**	**e**	**E**	**E**	**E**	**E**
Planetary probe S/C technologies					**e**	**e**	**E**		
***In situ* sensing of surface and atmospheres**	**E**				**e**	**E**	**E**	**E**	**E**
Components and miniaturization	**E**	**e**	**e**	**e**	**e**	**e**	**E**	**E**	**E**
Remote sensing	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**	**e**

Legend: E = enabling, e= enhancing (reduces cost and/or risk, increases performance) Spacecraft Systems); *need RPS or radio science for carrier-relay spacecraft that delivers probe.

Table 1. Technology Priorities for Outer Planet Exploration.

	Technology	Priority	Comments
Spacecraft Systems	**Power**	UP	Radioisotope power systems would be needed for the next Titan/Enceladus Flagship mission, requiring a sufficient supply of ^{238}Pu. Advances in power conversion efficiencies would reduce the quantity of ^{238}Pu needed for a given power requirement, along with a mass savings.
	Transportation	1	Electric propulsion would be strongly enhancing for most OP missions, including a Titan/Enceladus Flagship, and aerocapture technologies would enable a Neptune orbiter mission. These technologies provide rapid access, increased mass and/or lower mission risk.
	Communications	1	The science return from every mission would benefit from improvements in communications infrastructure, including Ka band and direct-to-Earth communications. *In situ* exploration with orbital assets would be greatly enhanced by improved proximity links.
	Planetary protection	2	New planetary protection approaches and technologies will be required to meet the anticipated requirements for *in situ* exploration to targets of interest for astrobiology.
In Situ Exploration	**Mobility and landers**	1	Access is critical to *in situ* exploration central to a Titan Flagship mission concept, making various types of mobility systems enabling, e.g., montgolfière balloons for Titan. Advances in autonomous mobility technologies could also provide alternatives for various New Frontiers mission concepts. Landers required with sampling acquisition and handling for Titan lake, dune & cryovolcanic regions.
	Extreme environments	1	The proposed missions span a number of diverse environments, requiring technology advances in fields ranging from low T and P, to high heat flux and pressure during atmospheric entry. *In situ* sampling and instruments would benefit from technology program.
	Entry systems	2	New propulsive landing systems would enable operations on satellites without atmospheres. Investments required in key technologies for entry systems and planetary probes :extreme environment systems, miniaturized and low power integrated sensors, transmitters, and avionics, thermal materials, power management systems, entry/descent/landing technologies & on-board processing.
Instruments	***In situ* instrument systems**	1	New technologies and instruments would be required for improved science return to targets of astrobiological interest, enabling the proposed Titan/Enceladus Flagship mission. The instrument technologies would require associated development in sample acquisition and handling systems. Advances in thermal management are critical. Instruments required for Atmospheric probe missions.
	Components and miniaturization	1	Every mission is either strongly enhanced or enabled by improvements in miniaturization and advanced component design. A Titan/Enceladus Flagship mission would be strongly enhanced by development of miniature long-lived, low power cryogenic electronics.
	Remote sensing instrument systems	2	All missions with orbital or extended aerial operations would be strongly enhanced by improved technologies for passive and active remote sensing and radio science. High resolution and sensitivity instruments that are low in mass and power are required for a Titan/Enceladus Flagship.

UP Ultimate priority—Without new Pu-238, no further exploration beyond Jupiter will occur subsequent to EJSM.

1 Highest priority—New developments are required for all or most future OP missions.

2 High priority—Either the applications are more limited or NASA could effectively leverage existing work.

Specific OPAG Recommendations

POWER

OPAG strongly recommends that NASA work with the relevant agencies to ensure that Pu-238 production provides enough material for future OP missions, and fully support the validation of the ASRG system for OP applications, including the development of small (milli-/multi-watt) radioisotope power generators for sensor networks. In addition, NASA should adapt and complement industry-developed advanced solar cell and array technology program, advanced battery technology, and advanced power conversion and distribution technologies program for OP missions.

TRANSPORTATION

SMD should continue its development of EP components and consider development of an off-the-shelf multi-mission SEP module (not only for the OP missions) that would be available to users with acceptable cost and risk constraints. Aerocapture development should focus on needs identified for Titan and Neptune, and risk reduction resulting in flight readiness is strongly encouraged to open up this mission enhancing, and for Neptune, enabling technology.

COMMUNICATIONS

NASA should expand the funding of communication and radio science technologies required for the OP, especially making Ka-band operational and furthering proximity and direct-to-Earth communication technologies.

PLANETARY PROTECTION

OPAG strongly recommends that PP requirements to the OPs be defined early, especially for Titan and Enceladus, and that investments be made to jointly develop solutions and technologies for PP and contamination control.

IN SITU PLATFORMS

OPAG recommends a sustained investment in this decade that would result in the demonstration of technical readiness for launch of a Titan balloon, and that NASA support the development of key autonomy capabilities required for a Titan balloon. Further, OPAG recommends that NASA invest in focused studies of Titan lander concepts and associated entry, descent and landing technologies, and mature the technologies necessary for surface sampling in different environments.

ENTRY SYSTEMS AND PLANETARY PROBES

OPAG recommends investments be made in key technologies for entry systems and planetary probes; extreme environment systems, miniaturized, low-power integrated sensors, transmitters, avionics, thermal materials, power management systems, entry, descent and landing technologies, and onboard processing.

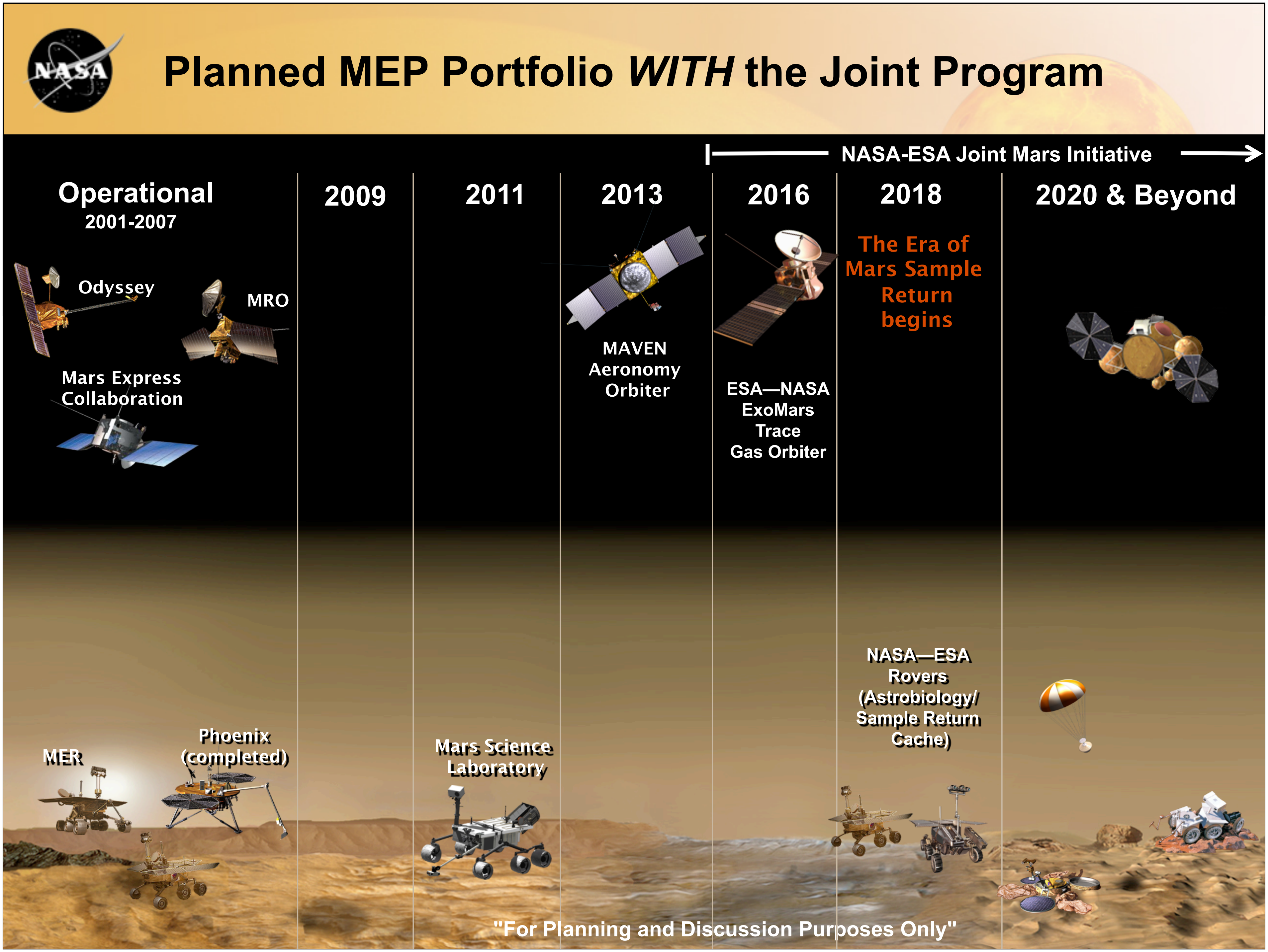
EXTREME ENVIRONMENTS

OPAG recommends that NASA fund a technology program focusing on designing and testing low (and high) temperature components and subsystems that could be used throughout the spacecraft (or probe) and instruments. Initiating this program as soon as practicable would have a major impact on the feasibility of a Titan Flagship mission and would also enable New Frontiers missions.

SCIENCE INSTRUMENTS

OPAG recommends that NASA initiate a well-funded instrument development program that goes beyond the present low TRL instrument development programs. To prepare for future OP missions, NASA should establish a focused program that matures in situ and remote sensing instrument system concepts to TRL > 6.

Technical/Technological Challenges for Multi-element Mars Sample Return Campaign


Planned MEP Portfolio WITH the Joint Program
NASA-ESA Joint Mars Initiative
Operational
2001-2007
2009
2011
2013
2016
2018
2020 & Beyond
Odyssey
MRO
Mars Express Collaboration
MAVEN Aeronomy Orbiter
ESA—NASA ExoMars Trace Gas Orbiter
The Era of Mars Sample Return begins
MER
Phoenix (completed)
Mars Science Laboratory
NASA—ESA Rovers (Astrobiology/ Sample Return Cache)
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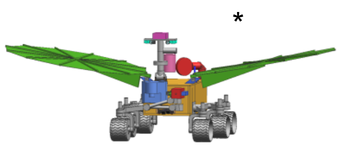
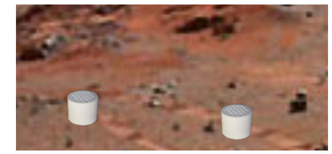
Functional Steps Required to Return a Scientifically Selected Sample to Earth



Sample Caching Rover (MAX-C)

Launch from Earth/Land on Mars → Select Samples → Acquire/Cache Samples



Sample Canisters On Mars Surface *

**

Mars Sample Return Lander

Retrieve/Package Samples on Mars → Launch Samples to Mars Orbit

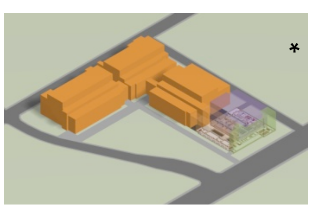
Orbiting Sample (OS) in Mars Orbit *

**

Mars Sample Return Orbiter

Capture and Isolate Sample Container → Return to Earth → Land on Earth

Orbiting Sample (OS) On Earth



Mars Returned Sample Handling (MRSH) Facility

Retrieve/Quarantine and Preserve Samples on Earth → Assess Hazards → Sample Science

Sample Science

**Note: Launch sequence of MSR-L/MSR-L can be switched: launching MSR-O first can provide telecom relay support for EDL/ surface operation/MAV launch

*Artist's Rendering

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Multi-element MSR Campaign Technologies

- **Tall pole technologies**
  - Defined as ***key*** technologies that require ***significant*** development
  - Sample acquisition and encapsulation (MAX-C)
  - Mars ascent vehicle (MSR lander)
  - Back planetary protection (MSR orbiter)

- **Other key challenges**
  - Round trip planetary protection (MAX-C)
  - Mobility capability (MAX-C and MSR fetch rover)
  - Terrain-relative descent navigation (MAX-C and MSR lander)
  - Rendezvous and sample capture (MSR orbiter)

Sample Acquisition and Encapsulation

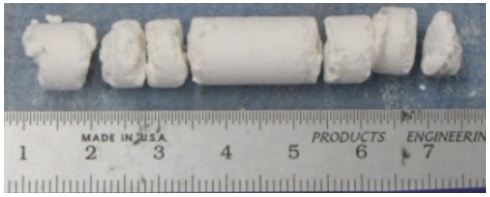
Consistent with MEPAG Next Decade Science Analysis Group (ND-SAG)

Science

- Acquire~ 20 rock cores with dimension approximately 1 cm wide by 5 cm long
- Store and seal samples in individual tubes
- Provide capability to reject a sample after acquisition
- Measure the sample volume or mass with 50% accuracy

Engineering

- System mass to be ~30kg
  - Includes robotic arm
- Sample on slopes up to 25 degrees
- Sample from a ~300kg rover



Examples of acceptable samples

Mars Ascent Vehicle (MAV)

MAV Target Requirements

- Launches 5kg Orbiting Sample (OS) into 500+/-100 km orbit, +/-0.2deg
- Ability to launch from +/- 30^{o} latitudes
- Continuous telemetry for critical event coverage during ascent.
- **Survive relevant environment for Earth-Mars Transit, EDL, and Mars surface environment for up to one Earth year on Mars**
- **300kg (including OS)**

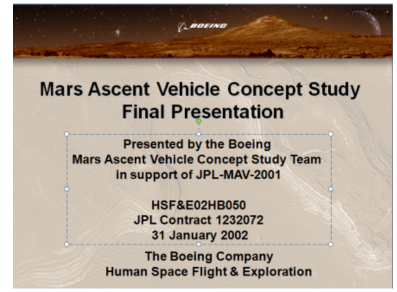
NASA has not launched a rocket from a planetary surface autonomously before.

Three industry MAV studies performed in 2001-2002

•Considered solid, liquid, and gel propulsion systems.

•Identified technology gaps, assessed risk, and provided estimates for mass, volume, and cost.

•Several follow-up reviews and RFIs have been conducted



Summary study results

•Solid propulsion was judged to be more reliable, simpler, and most mature

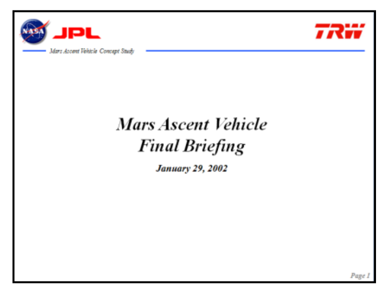
•MAV components are available, but are not developed for long-term storage in relevant environments (including thermal cycling) or for EDL g-loads.

- Long term martian surface storage more demanding than typical storage in space

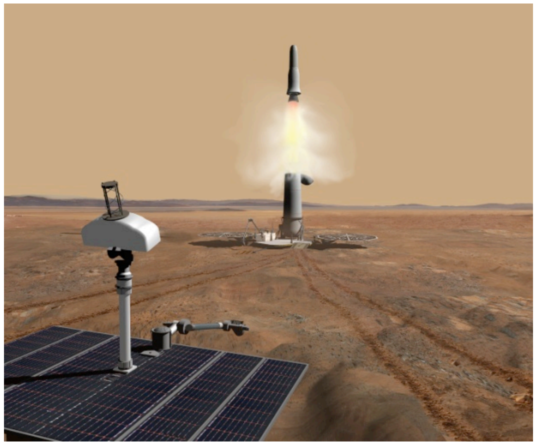
•Mass estimate assessment ~300 kg

•Preliminary cost assessment for TRL 6 development

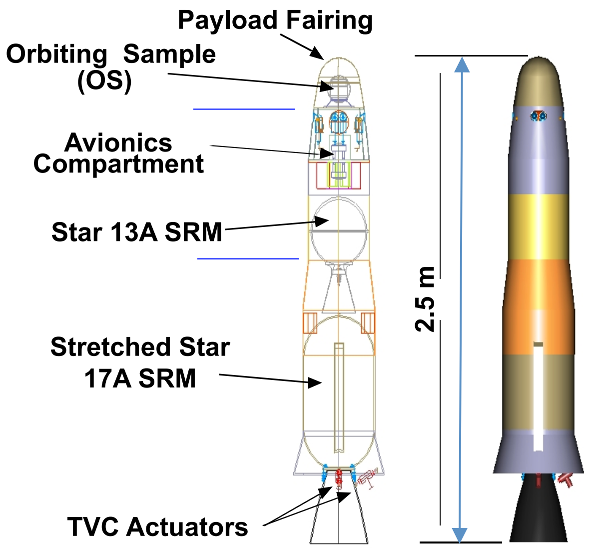
- Design/development including environmental qualification, ground and high-altitude flight tests ~$250M (adjusted to $FY15 with 50% reserves)



Solid Two-Stage Mars Ascent Vehicle Concept*



All figures are artist's concepts



- Kept thermally stable in an RHU-augmented thermal igloo.
- Continuous telemetry for critical event coverage during ascent.
- Fully redundant C&DH
- Uses standard and stretched solid rocket motors (SRMs). Same fuel as MER and Pathfinder descent motors.
- Flight time to orbit ~700 sec
- 3-axis stabilized
- Stage-one uses a Thrust Vector Controlled nozzle
- Stage-two uses a fixed nozzle. Steering is accomplished by the use of four pairs of 20lbf hydrazine engines (primary and backup)

* LMA 2002 study

Strawman Development Plan

- **Phase 1: Early investment (~$3M funded by In-Space Propulsion ROSES NRA, start date ~10/1/2010)**
  - System definition and development studies (~6 months)
  - Propulsion subsystem development and tests for select MAV concepts (~3 years)
- **Phase 2: Component technology development to TRL 6 and system architecture downselect (~2 years, ~$40M, may include ISP follow-on options)**
  - Develop component technologies to reach TRL6
  - Test components' performance in realistic temperatures, storage, EDL g-loads as appropriate
  - Culminates in the final downselect to a single concept, whose high-risk components have known performance and survivability characteristics
- **Phase 3: Integrate and develop a MAV. Perform integrated testing and qualification. (~3 years, ~$210M, includes ISP Phase 3 options)**
  - Perform three high-altitude flight tests to assure at least two successful tests and measure performance prior to MSR lander PDR.
  - At least one flight test must be performed on unit that has successfully completed environmental qualification/life testing
- **Flight Project responsibilities, after completion of technology program:**
  - Update design based on test results, fabricate flight unit hardware, spare, and interface test articles (mechanical, electrical/testbed), complete flight acceptance test, and deliver to ATLO

Back Planetary Protection

Planetary Protection

Requirements & Mission Scenarios

Forward PP

Outbound to Mars

Avoid contamination of Mars with Earth life

Introduction of viable Earth life into a favorable martian environment is considered harmful contamination by definition

Round Trip PP

Avoid false positive life detection event

Life detection event in this context is considered to mean detection of contamination that could be confused with extraterrestrial (ET) life

Back PP

Outbound to Earth

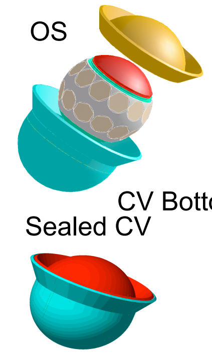
Protect Earth from potentially harmful effects

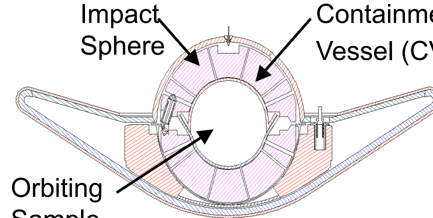
(biohazards)

Target Requirements

- **MSR is a Restricted Earth Return mission**
  - Goal of $<10^{-6}$ chance of inadvertent release of an unsterilized >0.2 micron Mars particle.

- **Subsystem requirements:**
  - **Break-the-chain of contact with Mars**
    - Deliver a “Mars contained” OS to Containment Vessel (CV)
    - Assure OS does not “leak”
    - Mitigate ascent and orbiter dust
  - **Sample container protection**
    - Reliable delivery to Earth entry corridor utilizing a robust Earth Entry Vehicle (EEV)
    - Assure containment at impact
    - Maximize OS , CV, and EEV meteoroid protection
  - **Quarantine in specialized sample handling facility and application of a test protocol to assess safety prior to release**





Earth Entry Vehicle (EEV)

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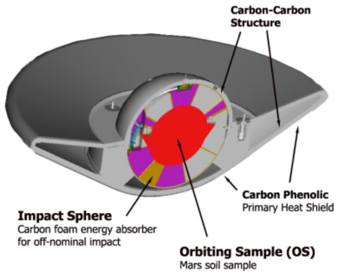
Current Capabilities/State of the Art

- **Probabilistic Risk Analysis (PRA) approach was developed to assess the overall probability of meeting the goal**
- **Preliminary design of the EEV was completed and a test article developed. Performed component and system tests:**
  - EEV drop test achieved terminal velocity and demonstrated shock tolerance.
  - Wind tunnel tests verified aerodynamics, including self-righting.
  - Arc jet tests verified TPS performance.



- **A brazing technique was developed to TRL 3 for containment assurance and breaking the chain of contact with Mars**

- **Leak detection**
  - OS leak-detection technique using wireless transducer was demonstrated at TRL3 via an SBIR
- **Sample container protection**
  - Preliminary materials for OS, CV, and EEV to assure meteoroid protection were selected (TRL 2-3 development).

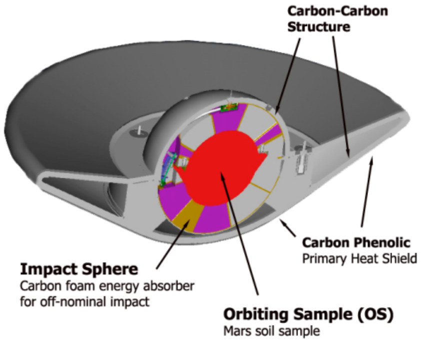
Strawman Development Plan

- **Update/improve models for Probabilistic Risk Analysis (PRA) to measure capability to meet goal**

- **Breaking-the-chain**
  - Investigate various options of sealing the OS in a container. Will implement and evaluate prototypes
    - Down select and develop technology to TRL 6. Test and verify sealing
  - Develop OS leak detection technique by considering pressure drop or other techniques
    - Down select and develop technology to TRL 6

- **Sample container protection**
  - Update EEV design considering the availability of TPS material
    - Perform impact, heat, and aerodynamics tests
  - Select materials for OS, CV, and EEV and satisfy meteoroid protection requirement

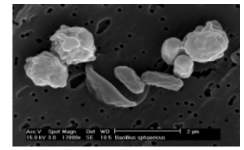
- **Assure containment and sample integrity during ground processing**
  - Sample transfer from landing site to Sample Receiving Facility
  - Ultra-clean sample manipulation, double-walled glove boxes



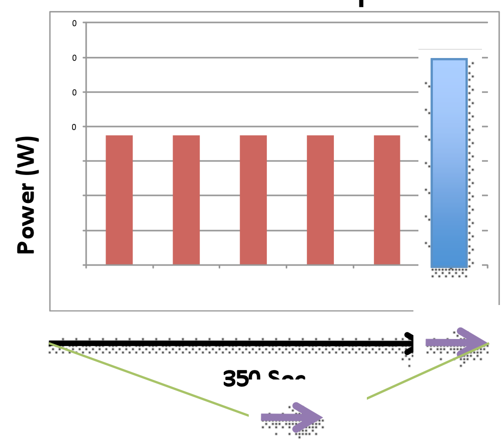
Other Key Challenges

Other Key Challenges

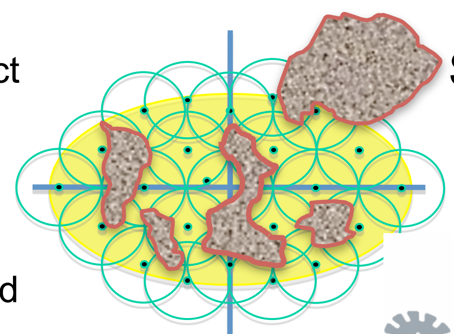
- Round trip planetary protection (MAX-C)
  - Objective: Avoid false positive life detection
  - Approach: Clean assembly, bio-barrier, analytical tool to compute overall probability of contamination
- Mobility capability (MAX-C and MSR fetch rover)
  - Objectives: Increase average rover speed and develop lighter/smaller motor controller
  - Approach: Use FPGAs as co-processors and develop distributed motor control
- Terrain-relative descent navigation (MAX-C and MSR lander)
  - Objective: Improved landing robustness
  - Approach: Use terrain-relative navigation approach for avoiding landing hazards. Leverage NASA ALHAT project
- Rendezvous and sample capture (MSR orbiter)
  - Objective: Locate, track, rendezvous, and capture OS in Mars orbit
  - Approach: Update system design, develop testbeds, and perform tests. Leverage Orbital Express capability



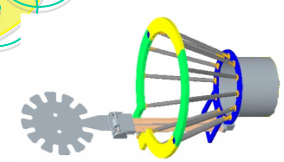
Round Trip PP



50 cm rover move timeline

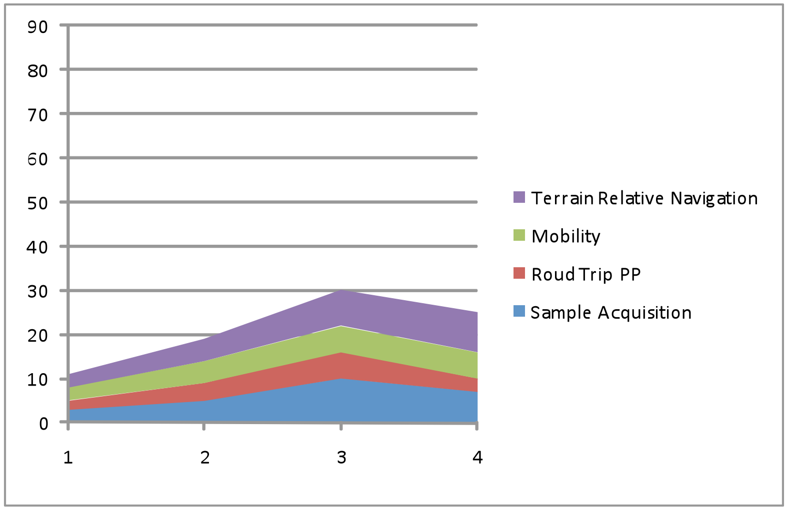


Safe Landing

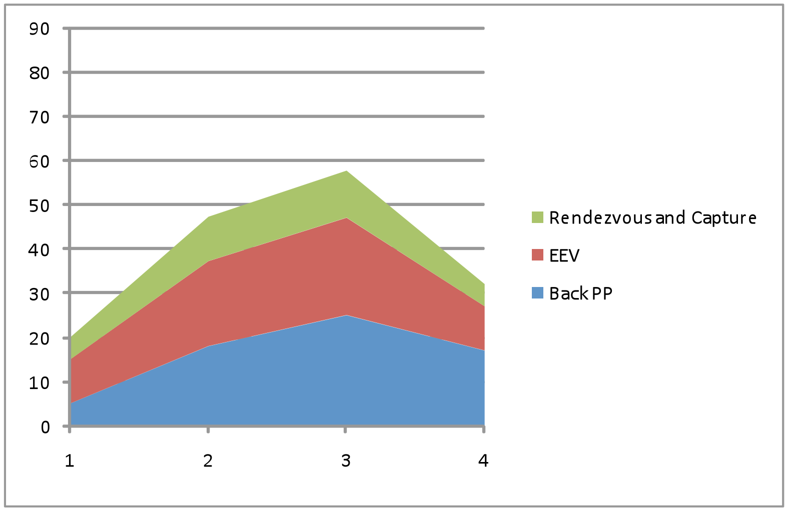


Sample Capture

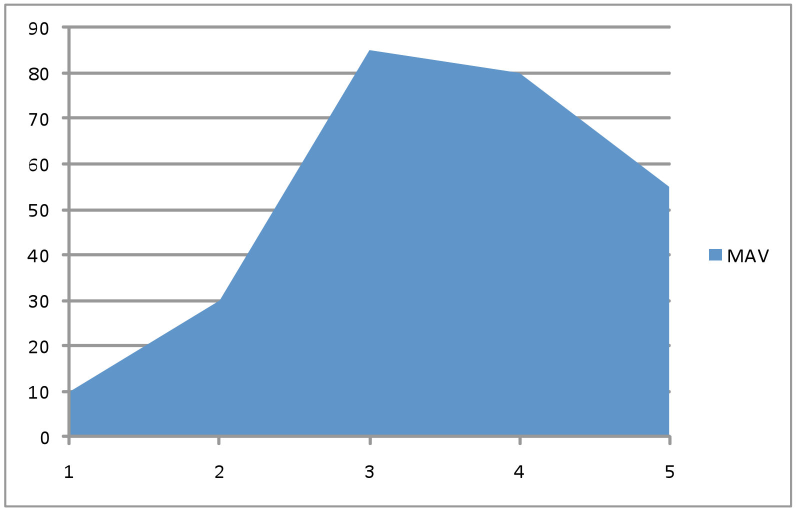
Estimated Technology Cost Including 50% Reserve ($M)



MAX-C ($85M)



MSR Orbiter ($160M)



MSR Lander ($250M)

"For Planning and Discussion Purposes Only"

Technologies for Future Venus Missions

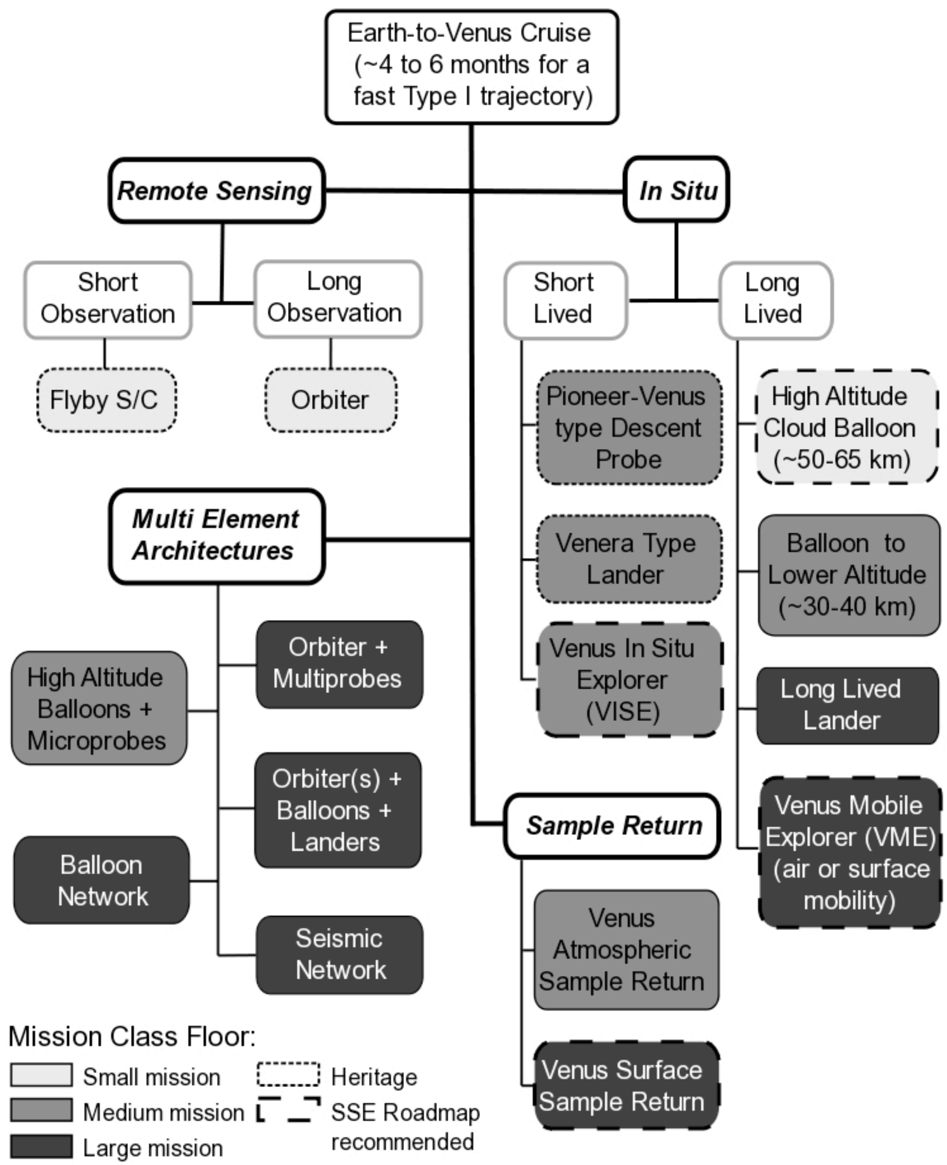
Tibor Balint
Jet Propulsion Laboratory
California Institute of Technology
and
Gary Hunter
Glenn Research Center

Presented at the
7th VEXAG Meeting
Irvine, California
October 29, 2009

Overview

- Introduction
  - Typical Venus Mission Elements and Architectures
  - Extreme Environments
  - Systems Approach for Component Protection
- Technologies for Future Venus Missions
  - High Priority Technologies (VFM)
  - Technologies for Short Lived Mission (presented by T. Balint)
  - Technologies for Long Lived Missions (presented by G. Hunter)
- Conclusions and Recommendations

Introduction: Mission Architecture Examples



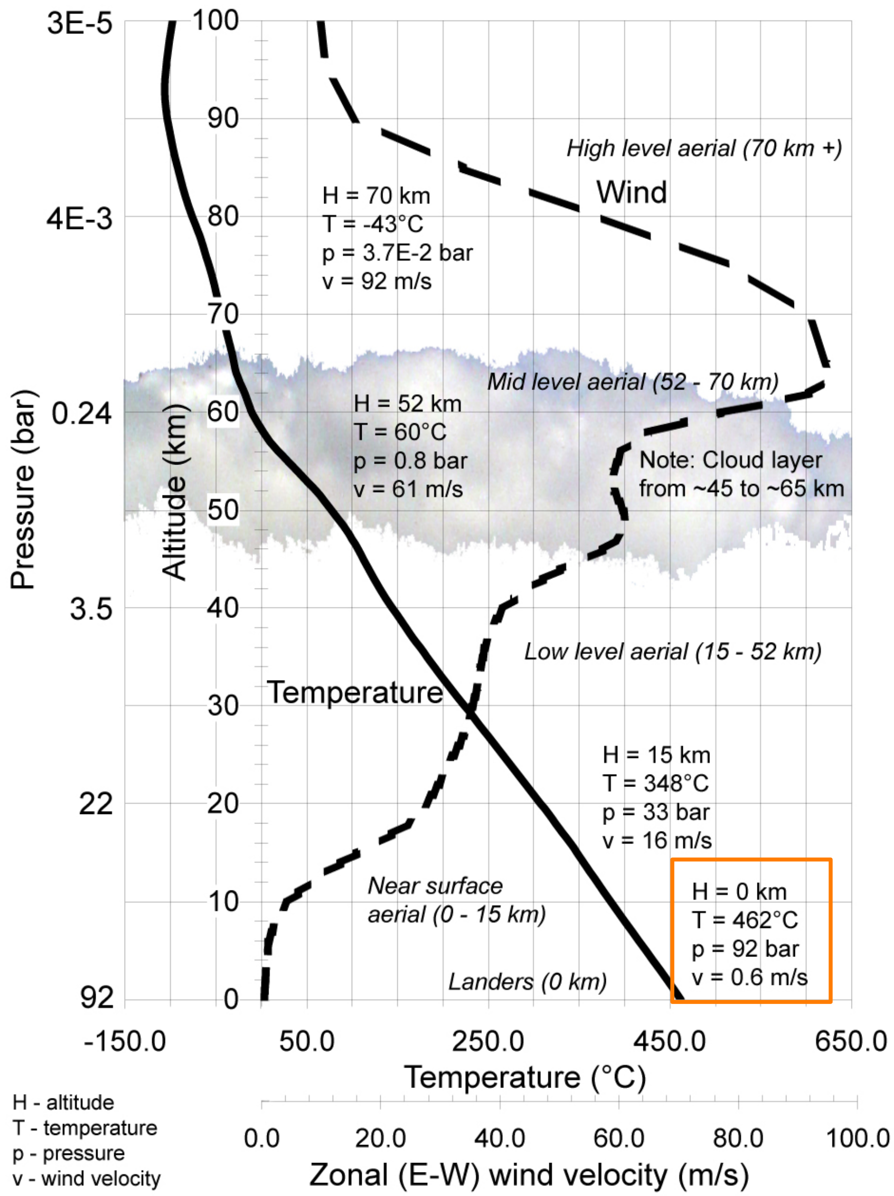
VDRM – Venus Design Reference Mission

- The Venus Flagship study included 17 candidate mission architectures

Venus Flagship DRM

- Multi-element architecture with short lived *in situ* elements
  - 1 orbiter (2 years)
  - 2 short lived landers (5 hours)
  - 2 short lived balloons (30 days)
- Enhanced mission
  - Increased lifetime
  - Hours
  - Days
  - Months

Introduction: Extreme Environments on Venus

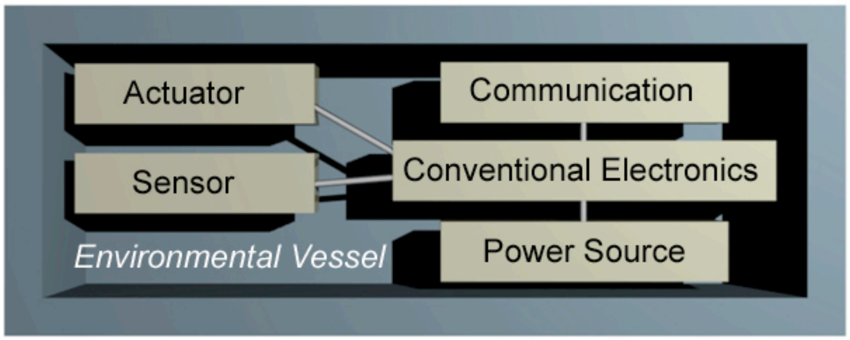


- Temperature and pressure increase towards the surface
- Sulfuric acid droplets in clouds
- Supercritical CO_2 near surface (12.5 km anomaly)
- Additional factors:
  - Mission lifetime
  - Interface with environment
  - Operations
  - Protection methods

Introduction: Systems Approach

Protection Systems

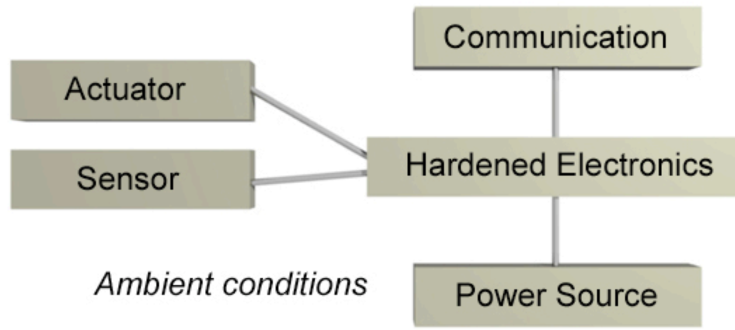
Use conventional components; Develop protection systems
(Thermal vessel; pressure vessel, radiation shielding etc.)



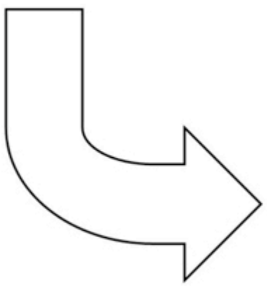
Impractical for planned missions

Component Hardening

Develop technologies tolerant
of extreme environments

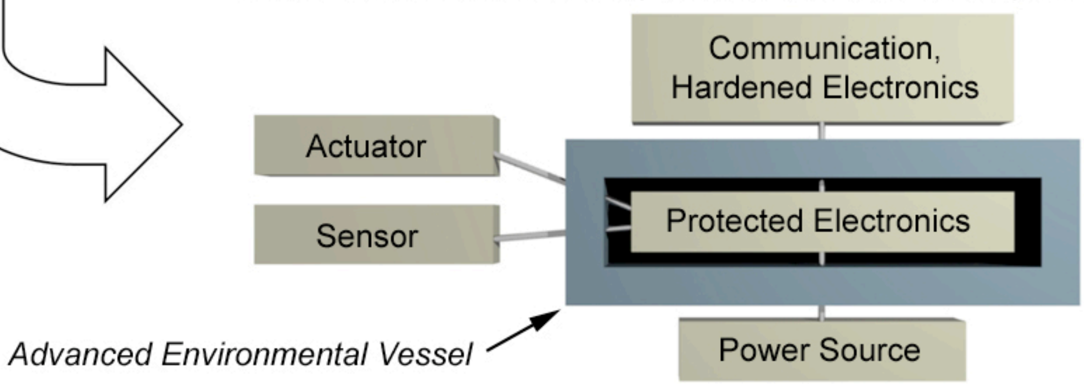


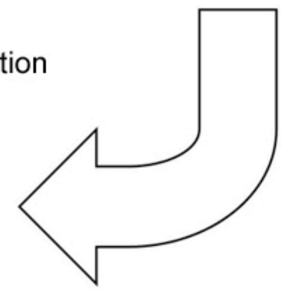
Prohibitively expensive for some technologies



Hybrid Architecture

Combination of hardened components and environmental protection



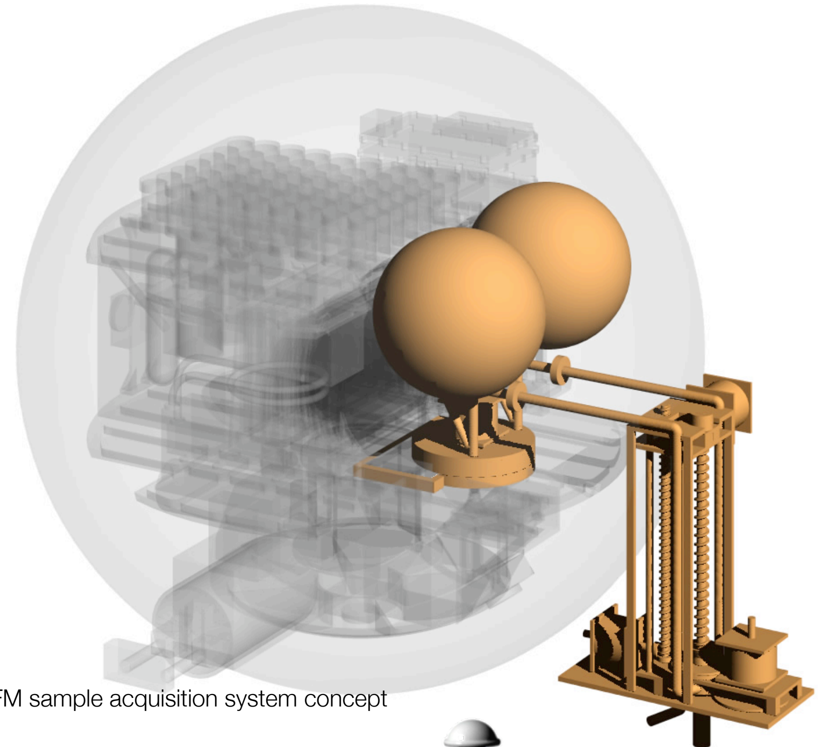


Requires development of innovative architectures

TECHNOLOGIES FOR FUTURE VENUS MISSIONS

HIGH PRIORITY TECHNOLOGIES

Surface Sample Acquisition & Handling (VDRM)



VFM sample acquisition system concept

Technology Development Needs

- surface sample acquisition system
  at high temperatures and pressures
- requires development for NASA

TRL 2 to 3 Priority HIGH

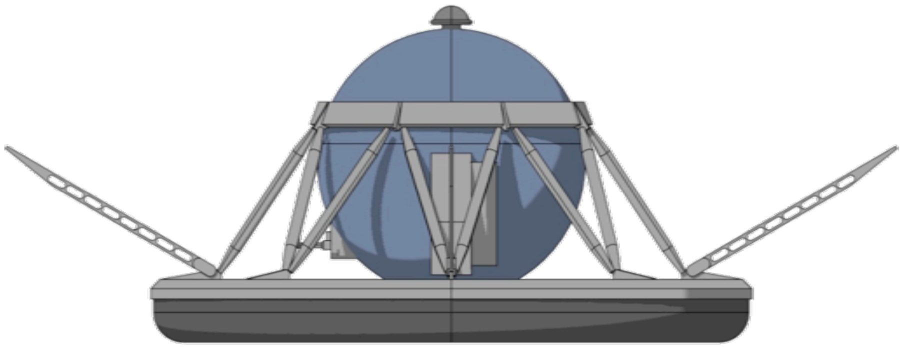
Rotating Pressure Vessel (VDRM)

Technology Development Needs

- full scale design and testing needed
- with a driver motor and
- mounted sampling system

TRL 2 Priority HIGH

Rugged-Terrain Landing (VDRM)



VFM lander with outriggers

Technology Development Needs

- design and test a landing system
- accounting for a large variety of unknown landing hazards
- using parachutes

TRL 2 Priority HIGH

Venus Test Facility (VDRM)

Small JPL Venus environmental chamber for testing materials and components (with window and electrical ports)

- large test chamber doesn't exist
- full scale *in situ* elements testing (probe/ lander)
- transient conditions and composition

TRL 2 to 6 Priority HIGH

TECHNOLOGIES FOR FUTURE VENUS MISSIONS

FOR SHORT LIVED *IN SITU* MISSIONS

Technology Development Needs

Pressure Control

- new lightweight materials
- advanced materials (e.g., beryllium, honeycomb structures)

TRL 4 to 9 Priority medium

Temperature Control (Passive)

- high performance thermal insulation for Venus environment

TRL 4 to 9 Priority medium

Advanced Passive Thermal Control

- alternate insulation and PCM needed to increase lander lifetimes beyond 2–5 hour

TRL 3 to 9 Priority low/medium

Power Storage

- adapt high T cell & battery designs for space
- address stability of seals and terminals
- minimize current collector corrosion at high T
- optimize the electrolyte composition to improve performance and reliability

TRL 4 Priority medium

Technology Development Needs

Atmospheric Entry at Venus

- re-establish test TPS capabilities
- remanufacture heritage CP;
- establish alternate to heritage CP TPS
- assess lower density TPS for Venus entry

TRL 3 to 9 Priority high/medium

Upper Atmosphere Balloons

- development, testing, verification and validation to address lifetime & reliability
- materials must tolerate high T, corrosive environment (H_2SO_4 droplets in clouds).

TRL 5 to 7 Priority medium

Near Surface Bellows

- build and test a metallic bellows system
- test it under Venus surface p/T conditions
- near surface operation must address altitude change and surface access
- requires other connected technologies

TRL 2 to 3 Priority medium

Technology Development Needs

Descent Probes

- Develop small drop sondes that could be released from a balloon platform (also work as ballast)

TRL 2 to 9 Priority medium

In Situ Instruments for the VDRM

- new *in situ* contact instruments
- several VFM instruments, e.g., heat flux plate, XRD/XRF, are at medium TRL
- high–T seismometry and high–T meteorology are at low TRL
- g–load tolerance during atmospheric entry should also be addressed

TRL 2 to 9   Priority medium

Orbiter Instruments and Telecom for the VDRM

- InSAR
- passive IR & millimeter spectroscopy
- cloud LIDAR

TRL 3 to 9 Priority medium

Technology Development Needs

Autonomy

- develop and test reliable autonomous operation for a Venus surface mission, including
- control of the rotating pressure vessel; drill site selection; sample acquisition; instrument operations; telecom

TRL 4 to 6 Priority medium

Cross Cutting Technologies

These technologies can benefit a number of planetary missions, e.g. probes to Venus and deep probes to the Giant Planets experiencing similarly high p/T

- thermal protection systems
- pressure vessel materials
- passive thermal control (insulation, PCM)
- instrumentation / miniaturization

TRL 3 to 9 Priority medium

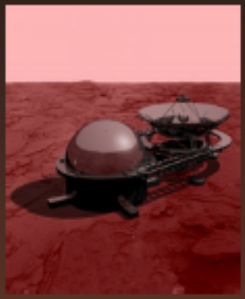
TECHNOLOGIES FOR FUTURE VENUS MISSIONS

FOR LONG LIVED *IN SITU* MISSIONS

STDT Final Presentation
Surface Science Enhancements

Seismometer and Meteorological Network

- Require long-lifetime measurements on the surface to
- Provide measurements of the size-frequency distribution of seismic events
- Surface meteorology with measurements such as temperature, wind speed and direction, and pressure
- Provide correlation between observed planetary events and changes in weather conditions



Long-Lived (months) Landers

- Sample multiple sites and multiple depths for a complete survey of the elemental composition, mineralogy, and chemistry of the landing site
- Acquire long-duration observations in time-varying phenomena like seismometry, meteorology, and wind
- Decrease mission risk and optimize science return by providing missions with complete instruments operation for extended period of time
- Humans in the loop during mission operation

Required technologies: Refrigeration, high temperature sensors and high temperature electronic components, balloon materials

Technology Development Needs for Long Lived Missions to Venus

- High and medium temperature electronics,
- High temperature actuators,
- Motors,
- Sensors,
- Power sources with active refrigeration,
- Telecom
- Seismometers
- High temperature balloon materials

Conclusions & Recommendations

- VEXAG recommends investments in key technologies to enable future Venus missions.
- The highest priority technology items, in line with the VDRM, are:
  - a sample acquisition and handling system,
  - a rotating pressure vessel,
  - a rugged-terrain landing system, and
  - a large scale Venus test chamber facility.
- A future Venus Flagship Mission could be further enhanced by
  - longer operating lifetimes on the surface.
- For this, development of additional technologies are needed, including
  - a Venus specific Radioisotope Power System, coupled with active cooling
  - high temperature tolerant components (e.g., sensors, actuators, and electronics)
- Other mission architectures could be enabled by technologies for
  - Seismometry; metallic bellows for near surface mobility; and a multi-balloon system for a future Venus sample return mission

Small Bodies Technology Recommendations

Primitive Bodies technology requirements vary with destination

- For primitive bodies such as comets and asteroids, the technologies required relate to the type of object studied and the mission scenario that enables the discoveries. For NEO Sampling, need
  - deployable assets (e.g., penetrators, rovers) for microgravity environments.
- Technologies for Main Belt Asteroids and Trojans investigations center on:
  - propulsion,
  - telecom,
  - Sensing and landing packages,
  - proximity operations
  - sampling mechanisms.

Small Bodies Technology Recommendations

- The strategy for Comet Exploration involves a strong technology development program that can enable sampling from depth in the nucleus, improved in situ analysis, and the return of nucleus material to Earth. Improvements should be developed
  - in S/C power systems,
  - propulsion technologies,
  - low power/lightweight instruments, including those that probe structure of the nucleus.

- The small satellites missions require new technologies in:
  - propulsion,
  - sensing,
  - guidance and control,
  - sampling
  - autonomy

Small Bodies Technology Recommendations

- The exploration strategy for the Ice Dwarf Planets would hasten development of mission-enabling technology in areas similar to the outer planet technology recommendations:
  - Electric power - ASRGs,
  - ^{238}Pu production;
  - Navigation - long distance ranging, autonomous GN&C;
  - Low mass flight systems and instruments and maintaining very deep space communications capabilities.
- Centaurs and TNOs missions require improved power systems for outer-SS trips.
  - Nuclear power would facilitate multi-object missions.
- Interplanetary Dust investigations require development of technologies for :
  - IDP collection and analysis and instruments that can monitor and accurately measure the zodiacal light.

Summary of AG Recommendations

Technologies required vary considerably with mission destination. Critical items are:

- development of power and propulsion systems that can take experiments to the far reaches of the solar system
- development of capabilities to ensure Mars samples can be returned to Earth safely
- Development of ‘program specific technologies’ including in situ technologies that can enable experiments on Titan, Venus, small bodies and eventually Europa.
- Aerocapture and planetary probe technologies also need to be advanced in order to provide a wider range of mission concepts to the scientific community

Additional Recommendation being considered outside of the AG's.

- Although none of the community assessment groups have high-lighted the need to re-develop nuclear reactors for space applications, it is clear that this is an alternative path in the event that ^{238}Pu production is not immediately forthcoming.
- Small nuclear fission reactors, using ^{235}U rather than ^{238}Pu are feasible for many robotic missions and recent developments in thermoelectric technology should allow simpler and more mass-efficient design.
- Use of such a reactor could enable more capable missions and allow use of electric propulsion at extreme solar distances, which could facilitate rendezvous and orbit insertion and possibly increase delivered mass for many missions.
- In addition, it could obviate the need for gravity assists to outer planets and provide frequent launch opportunities.
- Nuclear thermal propulsion, using hydrogen as the working fluid, is also being considered for the manned mission to Mars and if we see robotic exploration as a first step toward combined human-robotic exploration then the development of high Isp, high thrust propulsion is also required.