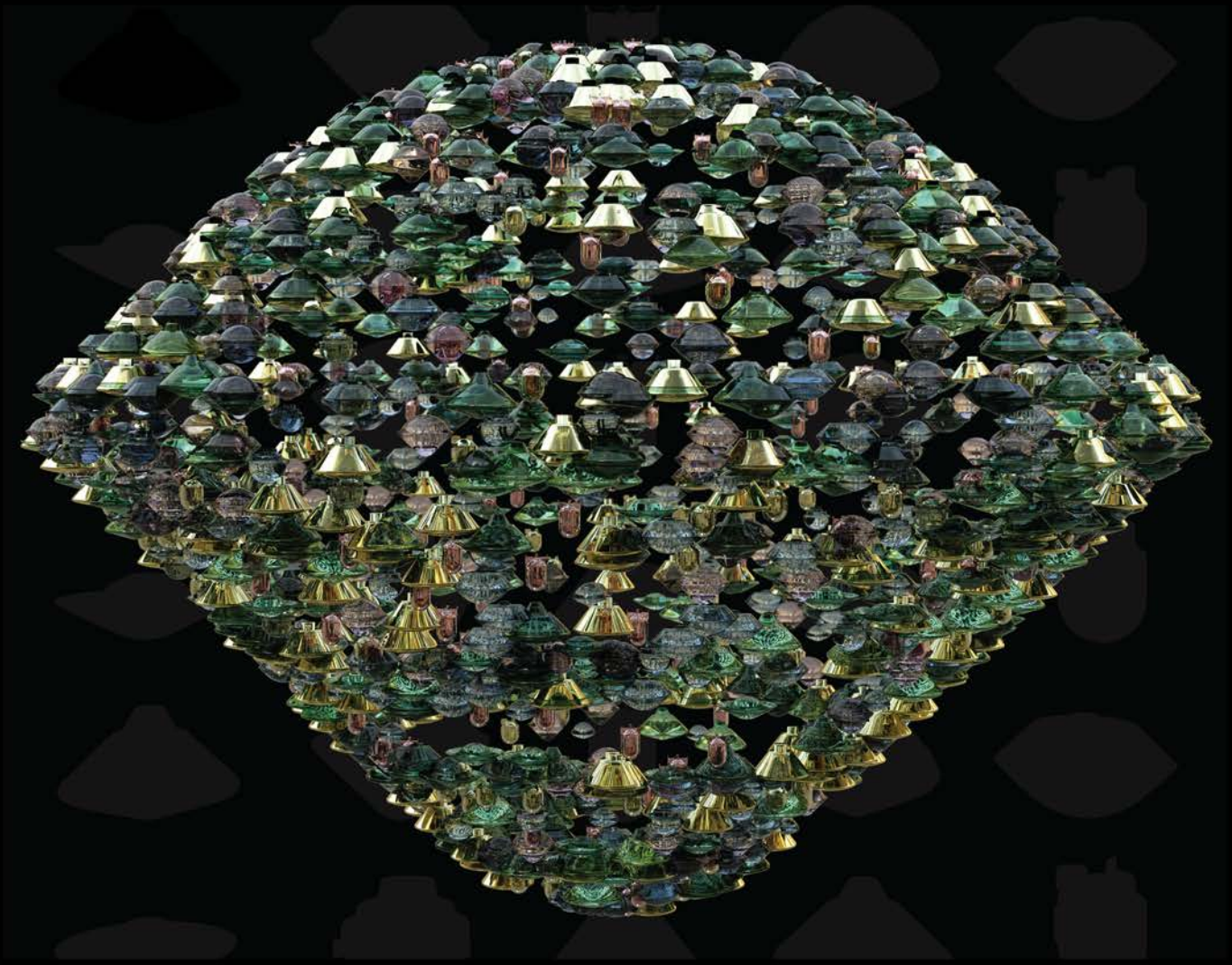
Science and Technology Progress Report on Planetary Probes



11th International Planetary Probe Workshop

Pasadena, CA, USA

2014

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Science and Technology Progress Report on Planetary Probes

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Foreword

By Bernie Bienstock, IPPW-11 International Organizing Committee Chair, Jet Propulsion Laboratory, California Institute of Technology

Although we have conducted eleven International Planetary Probe Workshops (IPPWs), we have not previously reported a condensed set of results and recommendations. Beginning with this IPPW-11 publication, we are publishing a Science and Technology Progress Report that summarizes the results of each workshop. Our findings are important to the international exploration community, for they present mission concepts, technologies, and ideas to stimulate creativity and foster international collaborations that are seeded at our annual workshops.

The IPPW developed in 1998 from meetings between Jean-Pierre Lebreton (of the European Space Agency [ESA]/European Space Research and Technology Centre [ESTEC]) and David H. Atkinson (of the University of Idaho). In anticipation of the entry and descent of the Huygens probe at Titan in 2005, the workshop was intended to be a one-time meeting dedicated to the study of planetary-entry probes and descent-trajectory reconstructions. Drs. Lebreton and Atkinson had a vision to bring together planetary scientists, spacecraft engineers, and mission designers with expertise, experience, and interests in the areas of entry-probe trajectory and attitude determination. Additional topics included aerodynamics and measurement of the aerodynamic (and aerothermodynamic) properties of planetary-entry vehicles.

The first workshop, entitled the "International Workshop on Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science," was held at the Instituto Superior Tecnico of the Technical University of Lisbon in Portugal in October 2003. Approximately 70 people attended. The first four-day event so inspired Ethiraj Venkatapathy that before the Lisbon event ended he volunteered to host a second workshop at the National Aeronautics and Space Administration (NASA) Ames Research Center (ARC) the following year. At the second meeting, in August 2004 (IPPW-2), Dr. Venkatapathy and his committee began a tradition of presenting a Short Course on the weekend before the workshop, now a successful feature of our annual meetings.

NASA's Planetary Science Division also first recognized the importance of the workshop for future technology planning at IPPW-2. Interactions between scientists and technologists at IPPW-3 in Athens, Greece, led to the recommendation of a Saturn probe mission that was ultimately included as one of the targeted missions for NASA's New Frontiers (NF) program. At

IPPW-4, held in Pasadena, California, the scope of the workshops was expanded to include technologies for handling the extremes of temperature and pressure in planetary environments; for entry, descent, and landing (EDL); and for sustained flight.

Additional IPPW traditions that have developed over the eleven IPPWs include the awarding of US and European scholarships to students recommended by professors in the field, as well as the bestowing of the peer-reviewed Al Seiff Award to a deserving leader in the field of planetary-entry probes.

The past eleven IPPWs have attracted almost 1800 professionals and students. In addition, nearly 600 people have benefitted from the Short Courses offered prior to the annual workshops. We have maintained our international theme, with five of the eleven workshops conducted at European centers of planetary probe exploration.

A word about the scope of our workshops. Although the word “planet” and “planetary’ appear throughout this report (as well as in our title), from our very first workshop and extending through IPPW-11, we have used the term to encompass not only solar system planets, but also their moons, as well as solar system asteroids, and comets.

As with most ongoing workshops and conferences, a core group of enthusiastic volunteers continues to serve on committees and devote their own time to planning and conducting our yearly events. We are proud of the work contributed over the years by our poster and oral presenters, as well as our Short Course instructors. We encourage you to read this first Technology Progress Report to gain insight into the wealth of ideas offered at this workshop; if you have interest in reviewing the material from previous workshops, you can find the presentations at http://solarsystem.nasa.gov/missions/ippw.

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1 Introduction

By H.S. Griebel[2] and A.L. Morris[3]

The IPPW brings together scientists, technologists, and engineers from an international community. Workshop sessions were intentionally organized such that a balance of science topics and technology topics were presented. This strategy resulted in a diverse set of eight session topics at IPPW-11 ranging from Science and Engineering Instrumentation to Entry, Descent, and Landing Technology. A balance was also achieved between US and non-US presenters and attendees to preserve the international flavor of the event.

IPPW-11 produced exciting presentations in the field of planetary probe science and technology and stimulated conversation with multidisciplinary contributions. This conversation was elicited by limiting author presentations to ten minutes, so that the bulk of the time could be dedicated to interaction, questions, comments, and discussion among participants. This report communicates the key points of discussions in each of the eight workshop sessions, including findings emerging from each, documenting the current state of the art and understanding of planetary probes as well as potential future developments. Presentations and posters featured in each session are listed in Appendix 1.

This report is available at http://solarsystem.nasa.gov/missions/ippw for professionals interested in the science and engineering of probe missions and for government decision-makers in a position to support such efforts.

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2 Missions

By Michael Amato[4], David Mimoun[5], and Bernie Bienstock[6]

This session focused on present and possible future probe and small-lander missions, as well as technologies supporting these missions. Papers and posters explored current mission results, the progress and status of missions in development, and the science goals and architectures for notional future probe and small-lander missions to solar system targets:

- The atmosphere and surface of Venus, Mars, and Titan
- Gas and icy giants, including Jupiter, Saturn, or Uranus
- Mostly airless bodies, including the Moon, Europa, and other smaller bodies

Talks and posters presented potential science drivers, mission designs, analyses of atmospheric trajectories, thermodynamic conditions, lessons learned from prior missions, application of nanosats to exploration, and technologies and testing to support solar system exploration.

The discussion at the end of the session focused on the risk associated with new and innovative technologies and mission design concepts, particularly the evaluation of risk during probe and small-lander mission selection processes. Considerable discussion centered on the question of how innovative mission designs using new technologies might move beyond the study phase in an environment that clearly favors flight heritage.

2.1 Introduction

Future probe and small-lander investigations rely on the development of a variety of innovative technologies to support the mission design and to enable remote sensing and in situ science. This was particularly evident when examining the requirements of different missions even to the same target. Three Mars mission concepts were presented, each of which faces a different challenge: (1) establishing a surface network of three science stations to characterize the planet's interior, surface environment, and surface-atmosphere exchange; (2) landing a 1200-kg

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vehicle to support sample retrieval; and (3) landing 50 metric tons to support human exploration. These three missions concepts require unique technologies, with little commonality in their mission implementation. In a similar fashion, the two Uranus presentations both featured notional entry probes, but they focused on different aspects of the mission concepts. One presentation focused on aspects prior to delivery of the entry probe, while the other explored different entry and descent scenarios, including direct ballistic entry and aerocapture techniques. Both techniques would require substantial heatshields, although the design details are highly dependent on the entry flight path angle. Finally, two Saturn mission posters highlighted different aspects of a potential probe mission to the gas giant. One explored the science goals of conducting a Saturn mission, while the other took a more general approach to such a mission with a discussion of the mission rationale, as well as options for the science instrumentation and probe design.

2.2 Relevant Missions and State of the Art

Presentations covered missions to a variety of targets and included work on missions that are currently under development or in an advanced planning stage, as well as advanced concepts.

2.2.1 *Potential Mars and Phobos Sample Return*

A current concept for Mars sample return science, first reported at IPPW-6, involves a three-mission architecture beginning with a rover the collects samples, continuing with a potential sample-return-and-launch mission, and culminating in a notional sample-return orbiter. Although there are currently no approved plans to return the Mars 2020 sample cache, a future sample-return-and-launch mission would have to access the same site as Mars 2020, and possibly use the same EDL system. Potential challenges are that the sample-return-and-launch system might be heavier than the Mars 2020 rover, and the future opportunity might not be as good as for Mars 2020.

The presentation by Kipp indicated that the Mars 2020 Sky-Crane EDL system would provide sufficient fuel to land 1200 kg, but with little development margin. Sites that are at or below 1 km beneath the Mars elevation datum (≤1 km as measured by the Mars Orbiter Laser Altimeter [MOLA]) should be reachable using existing capabilities. Higher-altitude sites (≥1 km MOLA) that may be desired for sample-return missions could still be accessed, but might involve delay for more favorable opportunities or new technologies such as the Low-Density Supersonic Decelerator (LDSD) parachute.

Phootprint is a concept for a Phobos sample-return mission that is a candidate mission in ESA's Mars Robotic Exploration Preparation Programme 2 (MREP-2). The rationale for a sample-return mission at Phobos rather than Deimos was discussed, with the science goal of understanding its formation and extrapolating the findings to our solar system formation. The Phobos mission sequence is illustrated in Figure 2-1. Discussion of the surface landing techniques included tradeoffs of hover-station approach vs. a direct approach. The pre-Phase-A study determined that it was feasible to collect and return to Earth a 100-g sample with a single launch. Technology

development efforts underway in support of this mission include a high-thrust apogee engine, landing gear, and sampling systems.

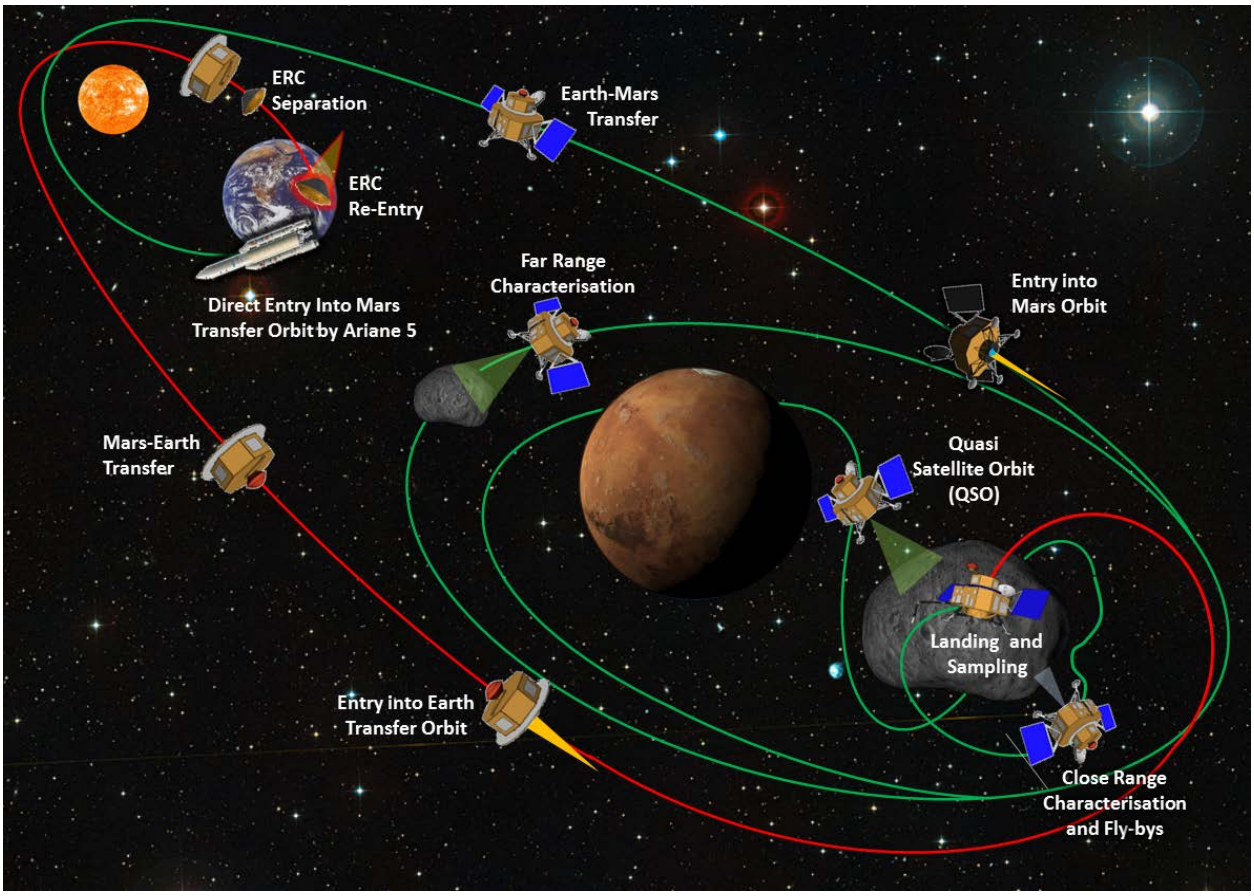

Figure 2-1. *Phootprint Phobos Sample Return—detailed mission sequence.*

2.2.2 *Conceptual Europa Penetrator Mission Study and Technology Demonstration*

Concepts for missions to the Jupiter system using ice penetrators developed by the UK-based penetrator consortium have been featured at IPPW since June 2012. Initially, their focus was on geophysical objectives at Jupiter's third Galilean satellite, Ganymede, and would have been deployed by ESA's Jupiter Icy Moons Explorer (JUICE) mission. However, for the last two years the focus has switched to the moon Europa, and the objectives have been broadened to include astrobiology as well as geophysics. The study reported at IPPW-11 included a design for a propulsion module that could be used to deploy a penetrator from a Jupiter orbit with close flybys of Europa—currently the architecture of NASA's proposed Europa mission. The results of rocket sled tests into ice deposits conducted at a test range in the UK were reported. A key advantage of the penetrator is that it would penetrate beneath the meteorite-impacted, exposed, and radiation-damaged surface of Europa to a pristine subsurface region. The presentation covered the design of a notional ice penetrator (Figure 2-2), as well as the testing conducted to verify its ability to penetrate to the desired depth.

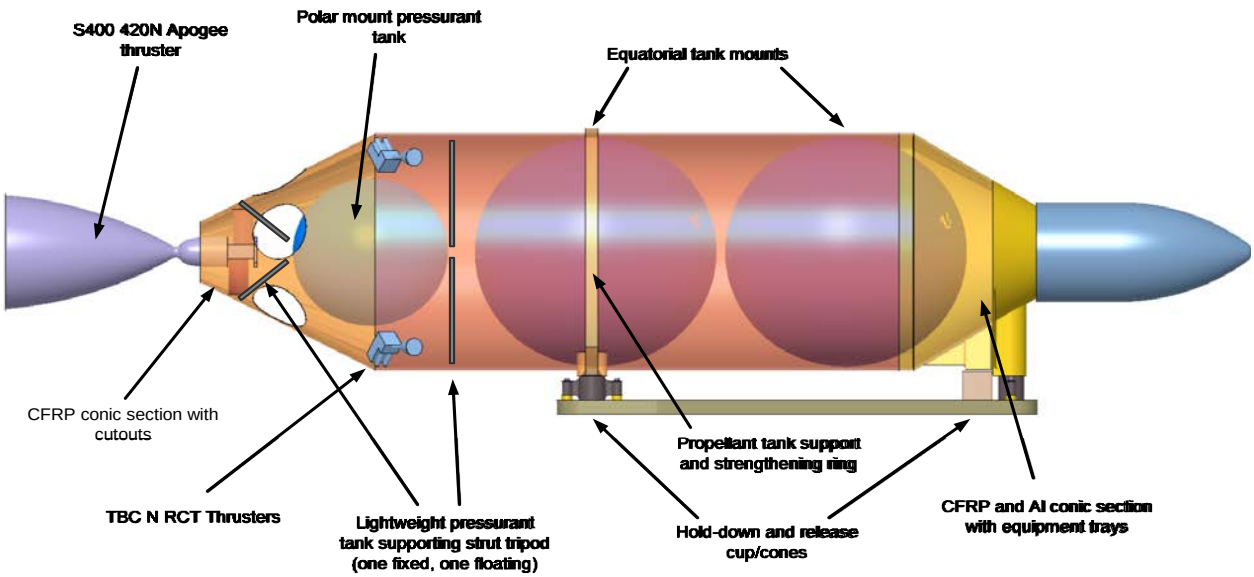

Figure 2-2. *Conceptual Europa penetrator descent module configuration.*

2.2.3 *Uranus Orbiter and Probe Concept*

Uranus was identified in the 2011 Planetary Science Decadal Survey as an important scientific target and the highest priority after Europa for a Flagship-class-mission consisting of a notional Uranus orbiter and probe. At that time, the proposed mission had a flight time to Uranus of 13 years and used chemical propulsion for Uranus orbit insertion. The alternative approach of aerocapture was not baselined because of technical immaturity and concerns about spacecraft packaging.

The first Uranus presentation—by a team led by Parul Agrawal of ARC with participation from NASA Langley Research Center (LaRC) and JPL—considered the aerocapture option more carefully and also examined the thermal-protection-system (TPS) requirements for the entry probe. Using a Cobra entry configuration with a lift-to-drag ratio (L/D) of 0.5 (see Figure 2-3), the team defined an aerocapture system for Uranus orbital entry that would provide a 50% mass saving over the chemical system baselined for the Decadal Survey. That advantage would be significantly greater for transit times shorter than the 13-year trip time defined by the Decadal Survey study. Another feature of this mission design was the deployment of the entry probe after the spacecraft attained orbit and not before. While this requires more propulsion, it would significantly ease the environment that the probe would experience and could allow Phenolic Impregnated Carbon Ablator (PICA) to be used for the probe as opposed to carbon phenolic or other high-performance TPS materials that have yet to be demonstrated.

A second Uranus presentation reported on the results of a study (conducted at the 2013 Planetary Science Summer School) of a Mission for Uranus Science and Exploration (MUSE). This mission concept opens the possibility of achieving many of the science goals of the Uranus Orbiter and Probe mission defined by the Decadal Survey with an NF–class mission. The team designed a mission with five orbiting instruments and four probe instruments, with cost savings

realized by obtaining the probe itself from a non-NASA partner. The estimated cost was $1.3B, a total close to the NF funding cap.

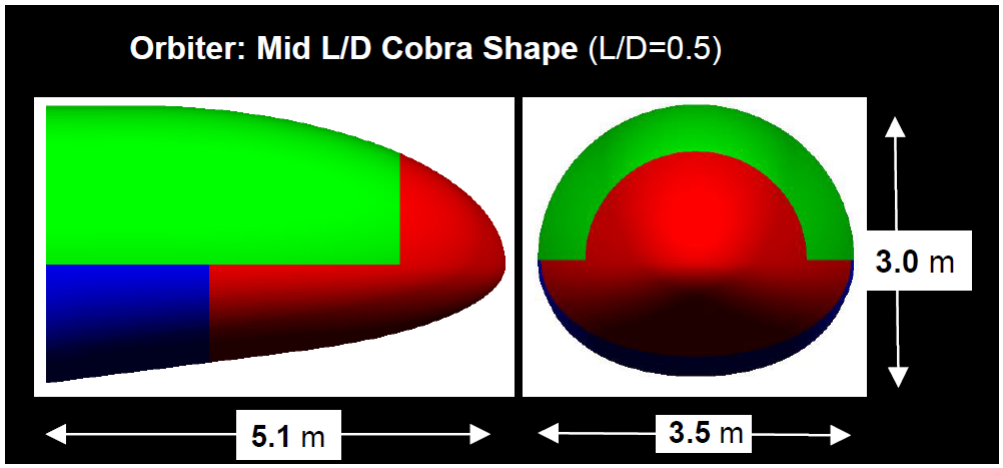

Figure 2-3. *Aeroshell shape studied for a Uranus orbiter mission concept using aerocapture. The dimensions were chosen to fit inside the Atlas 551 launch shroud. The value of L/D was based on past Venus and Saturn studies but needs to be validated by in-depth analysis.*

2.2.4 *Saturn Probe Concept*

A Saturn Probe has been a long-standing interest for the International Planetary Probe Workshop. At IPPW-3 in Greece, there was a resolution in favor of a Saturn Probe mission concept under a NF mission AO, and in 2011 the Planetary Science Decadal Survey added a Saturn Probe to the mission list for NF4. This is the first addition to that list since it was originally defined in the previous Decadal Survey. On the European side, a team has been advocating the Saturn Probe for ESA's Cosmic Vision M-class (i.e., medium-sized) mission (M4). Two contributions during IPPW-11 dealt with science for a Saturn Probe. From the US, Dave Atkinson and others described the science for a conceptual Saturn Probe for the NF4 opportunity. O. Mousis and members of an international team described the science for the proposed M4 mission. The NF4 opportunity is still pending; ESA has made its selections for M4, and no planetary mission was included.

2.2.5 *New Control Technology Concepts*

Two new spacecraft-control technologies were presented with the potential for enabling new mission capabilities. The first of these is an architecture for trajectory control for Adaptive, Deployable Entry and Placement Technology (ADEPT). Two of the four approaches identified in the presentation are illustrated in Figure 2-4. They have applications to human Mars missions and to aerocapture missions at the outer planets. The second technique—Spiral Thrusting—is applicable to electric-propulsion planetary missions in which swirl torques create challenges for long periods of thrusting. Other concepts covered in the session included a new concept for a Mars Network mission developed in Europe, which is seen as a companion mission to Phootprint in the ESA MREP program. The team from Northrop Grumman Aerospace Systems (NGAS) and L'Garde Inc. reported on recent developments in the notional Venus Atmospheric Maneuverable

Platform (VAMP) referred to as Lifting Entry/Atmospheric Flight (LEAF) technology. In this mission concept, the same inflated structure is used both for entry and for buoyancy after entry. Finally, Ralph Lorenz reviewed the science that could have been accomplished by the proposed Titan Mare Explorer (TiME) mission, a Discovery Step 2 candidate that would have explored the hydrocarbon lakes near Titan's north pole. Seasonal change in the Saturn system means that this mission will not again be possible until after 2040. Using Cassini, scientists have now accomplished a majority of TIME's science goals.

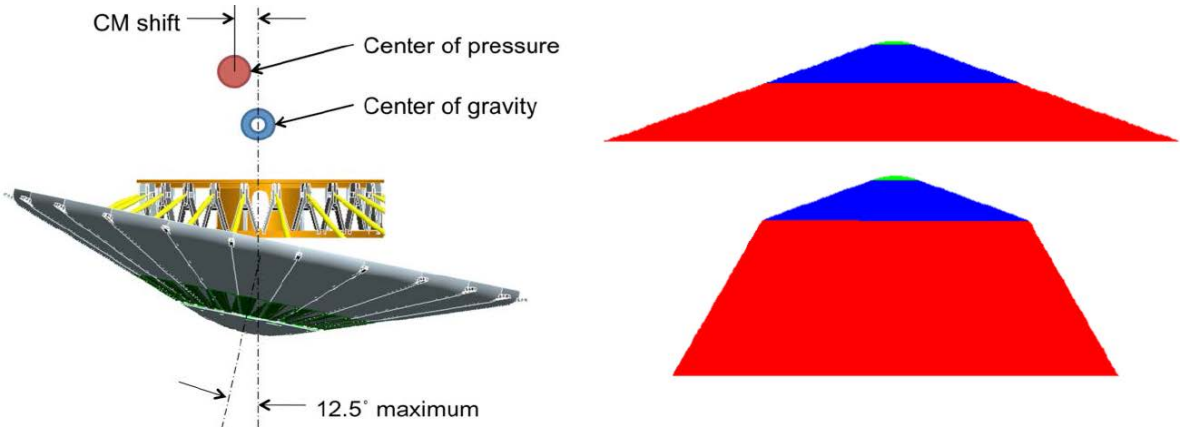

Figure 2-4. *Two of the control strategies investigated for trajectory control for the ADEPT architecture: Modulation of the bank angle and angle of attack by gimballing the aeroshell (left) and modulation of drag by adjusting the frontal cross-sectional area of the aeroshell (right).*

2.3 Mission Panel Group Question and Discussion Summary

Two primary questions were used as a starting point for the panel at the end of the session. The discussion varied from the nature of risk in probe missions to the nature of how risk-taking is reviewed, encouraged, or discouraged. The first discussion question was

- What mission-enabling design and science attributes or features create the most implementable or selectable probe on small-lander missions?

The resulting conversation quickly centered on the level of risks that would still be acceptable in a competitive mission-selection process, and which of those would then be sustainable for Flagship and larger missions. The expectation of high technology readiness level (TRL) and very low risk might be unsustainable for future probe or lander missions if destinations beyond those previously explored or planned are targeted. Technology required for the next generation of demanding science missions is necessarily innovative, and therefore should be expected to have a lower TRL than technologies currently applied to today's missions. In order to target challenging new areas of exploration, we must accept some level of risk. However, with explicit and prudent technology plans, this objection could be overcome. The discussion then focused on the characterization of a reasonable level of risk. Additional conversation explored how technologies, science, and other attributes could be influenced by politics, raising the acceptability of lower-TRL technologies to enable additional scientific return. It was hoped that the promise of significant, well-defined, novel science returns could increase governmental

agencies' acceptance of technical and cost risks. Education and training of the technical community are of utmost importance in this model.

The second discussion question followed from the need to advance technology to enable exploration of new destinations:

- Are lander missions focused on or driven by technology development a good idea, or should science be the main design driver for all landers?

One of the interesting discussion points on this topic was that technology development in the form of flight demonstrations might be necessary. There was some underlying discussion related to the ExoMars experimental lander carried by the 2016 orbiter, which features a small science payload. Many technology developments relevant to probe and lander missions have much to gain from well-planned flight demonstrations, as on Sojourner. A valid compromise is to encourage the flight of risky new capabilities as flight demonstrations on chosen missions. Cross-over science and technology missions can be very desirable if the right balance is struck between risk and mission return. Examples include the addition of desirable science results to technology-driven concepts, and infusing technologies or adding demonstrations to science-driven flight projects, as currently implemented in NASA's Discovery Program.

The most innovative probe or small-lander missions will require new methods of risk-assessment and risk-handling, and possibly a tailored review process. Technology-demonstration evaluations might be different from those of strictly scientific missions but governmental agencies and the public who support our missions should be encouraged to accept the concept that a risk–reward trade is attractive and worthwhile.

2.4 Opportunities and Future Development

Designs that enable more difficult missions are important to pursue. As new mission concepts and the technologies of today became incorporated into the designs of the flight missions of tomorrow, many areas of risk- and cost-assessment require reevaluation. Engineering areas that would benefit most include entry systems, novel materials, solar-electric propulsion and related flight dynamics, small landers, hazard avoidance, and mass- and power-reduction. For these advancements to become a reality, the willingness to accept risk must increase.

2.5 Findings

The missions presented in the Missions session were distinguished by their diversity, which drives the need to invest in needed technologies. Specific findings are summarized below:

1. To meet the challenges and reduce the risks of difficult future missions, an increasing number of technology demonstrations should be planned. In recognition of this long-term effort, technology maturation plans should span a reasonable number of years and be funded to produce the desired results leading to successful missions. *Continuity* of funding is as critical as sufficient funding for any one mission.

2. Sample-return mission concepts present significant implementation challenges driven by such factors as atmospheric density, gravitational fields, desired landing sites, and mass of the returned sample. There is a striking contrast between the design of a mission to return a sample from Mars (with Mars 2020 as a precursor) and that of a mission to return a sample from the Mars moon Deimos (as in the Phootprint mission), which does not have an atmosphere. Technologies must be developed to meet these challenges.
3. As documented in Vision and Voyages, missions to deploy probes at Uranus and Saturn would be critical to understanding the atmospheres and structures of the Ice Giants. Probe delivery and survival are key considerations that drive the probe heatshield design. Two mission concepts each at Uranus and Saturn provided a perspective of the mission and hardware design concepts to accomplish these high-science-return missions.
4. Probe missions call for innovative technology to deliver the science instruments to their atmospheric descent mission as well as innovative mission design to deliver the host spacecraft to the target planet. Inefficient historic heatshield designs greatly limit the instrumentation that can be delivered. Innovative heatshield concepts are required to maximize the science return. Science return from environments at extreme hot and cold temperatures is challenging, with risk management a key consideration.
5. Rocket sled tests of an ice probe have been successfully conducted in the UK. The probe could be a key component of a Europa Penetrator mission concept that would implant the vehicle in the subsurface of Europa in order to perform geophysical and astrobiological measurements. The possibility that this penetrator could be deployed from the proposed NASA Europa mission is being explored.
6. Control of in-space transportation systems can enable new missions and more efficient execution of existing ones. A spiral thrusting technique has been developed for accommodating swirl torques in electric propulsion systems. Several approaches have been identified for attitude and trajectory control of deployable aeroshells.

3 Science and Engineering Instrumentation

By B.J. Bienstock[7], S.W. Asmar, and H.S. Griebel[8]

Planetary-entry-probe missions are flown to deliver instrumentation to a planet or planetary body to conduct in situ scientific investigations, in many cases while descending through the atmosphere to the surface. These investigations generate data that are transmitted to Earth, or return physical samples of the body for analysis in Earth laboratories. Since science instrumentation requirements are key design drivers for planetary probes, it is important that mission planners, payload designers, engineers, and managers understand the basic characteristics and operations of probe instruments. It is important that the engineering community understands the basics of the scientific goals and science instrumentation, and that the science community understands the practical engineering limitations on the data- or potential physical sample–return.

3.1 Introduction

The purpose of the session was to focus on typical science instrumentation flown on probe missions. The session reviewed current projects and studies, details of science instrument concepts and designs, and associated science goals and results. In addition, lessons learned from science instrumentation on earlier missions were summarized, along with plans for future probe missions.

3.2 State of the Art

Paul Mahaffy [1] reviewed the state of the art in contrast to the instrumentation first flown on the Pioneer Venus and Galileo probes. Measurement of isotopes is a prime science product obtained via instrumentation ranging from the Galileo Probe Mass Spectrometer (GPMS) (Figure 3-1) to Curiosity's Sample Analysis at Mars (SAM) suite (Figure 3-2). Ever more sophisticated instrumentation, with a myriad of valves, pumps, heaters, ovens, capillary leaks, and enrichment systems, allows increasingly accurate measurements over an ever wider range

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of isotopes. The advancement in instrument sophistication is dramatically illustrated by comparing the complexity of the GPMS with the SAM suite flown on the Mars Science Laboratory (MSL). Isotope measurements, in turn, allow scientists to understand how terrestrial planets other than Earth lost their atmospheres and to understand the age of the current atmospheres and hence of the planetary bodies they surround.

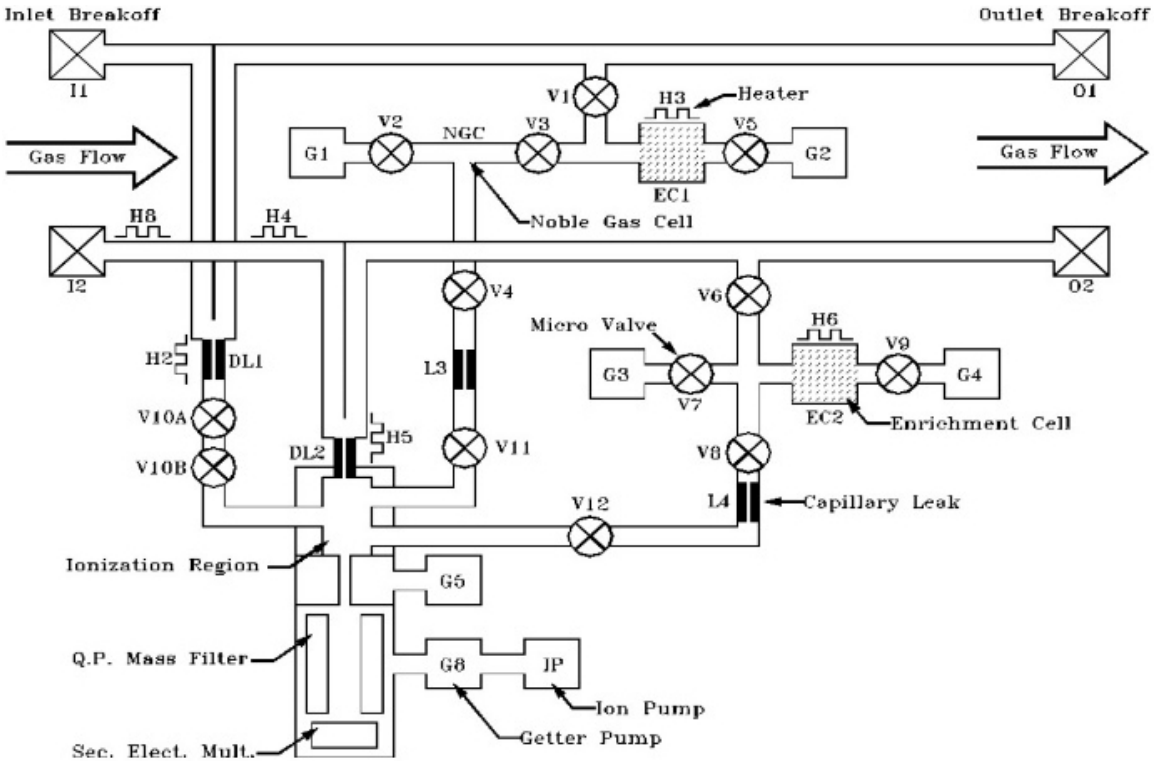

Figure 3-1. *Galileo Probe Mass Spectrometer schematic [1].*

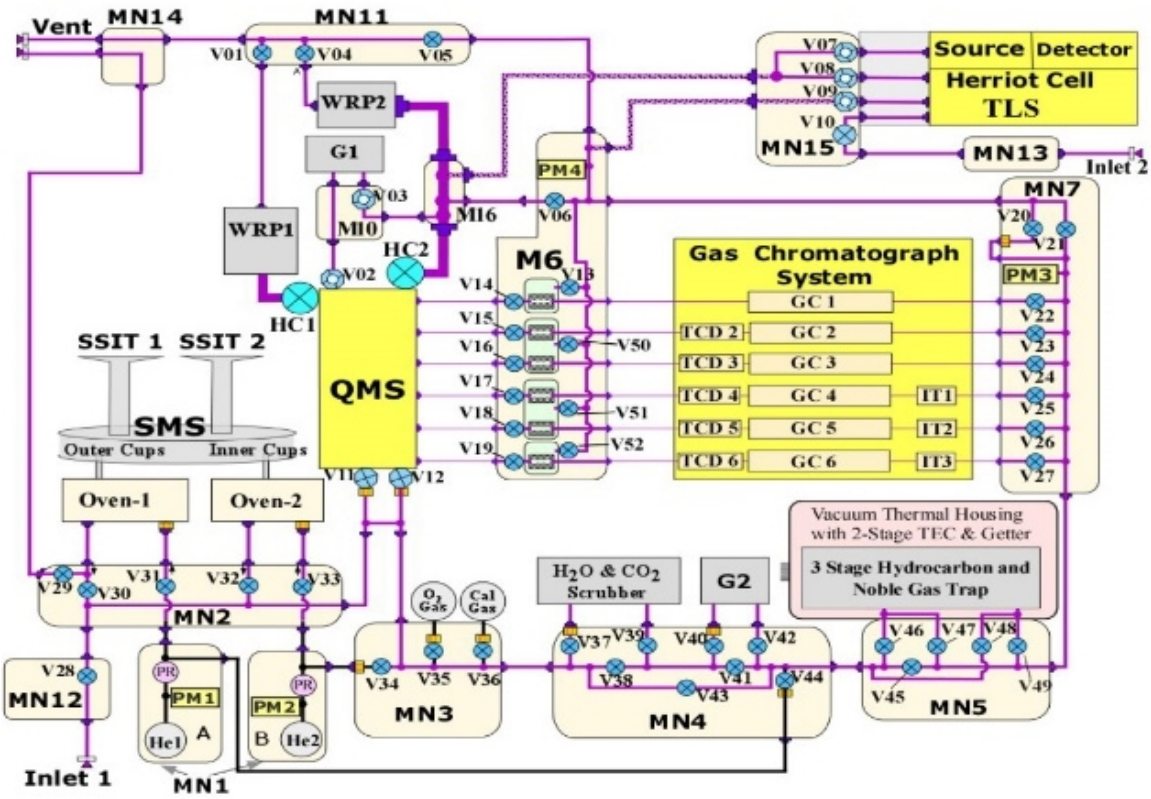

***Figure 3-2**. MSL Curiosity Sample Analysis at Mars instrument suite schematic [1].*

Instrumentation of heatshields is imperative for both the engineering and science of planetary-entry missions. Two presentations by Trifoni [2] (Figure 3-3) and Guelhan (Figure 3-4) [3] discussed this topic, which has been the focus of many IPPW presentations in the past. Omaly's poster elaborated on proposed instrumentation for generating complementary engineering and science data from heatshield instrumentation. Detailed measurements of heatshield performance parameters enable validation of heatshield designs, which is critical for aerothermal and aerodynamic modeling and feeds into future design decisions. In situ measurements from planetary-entry missions with instrumented heatshields allow future missions to consider a less conservative and more economical heatshield design. Since data-return from a mission also amounts to flight-proving a particular heatshield design, heritage can be incorporated to benefit the design of more capable future probes. Finally, performance data from the heatshield instrumentation allow an independent check of the atmospheric parameters as generated by the science instruments. During the post-session discussion, attendees were quite vocal in their support of requiring measurement of these parameters on all future planetary-probe missions.

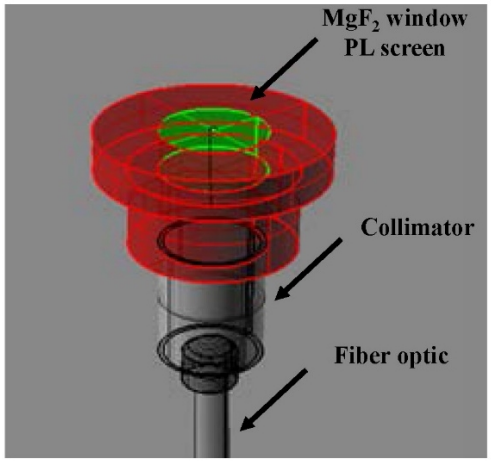

Figure 3-3. *Photoluminescent sensor [2].*

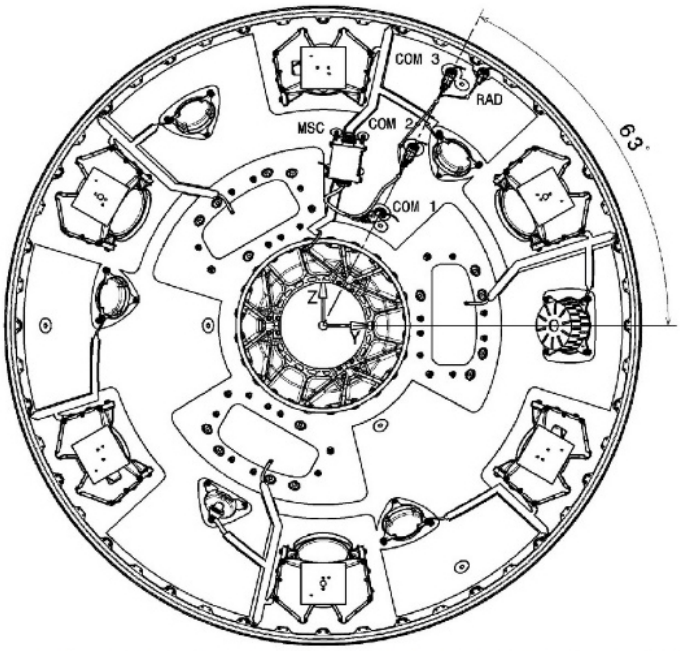

Figure 3-4. *COMARS+ payload on EDL Demonstrator Module (EDM) back cover [3].*

Other instruments and payloads were discussed in Zacny's presentation [4], which described the innovative drilling and caching techniques Honeybee Robotics is proposing for the Mars 2020 mission. An example of Honeybee's design is provided in Figure 3-5. Asmar's paper highlighted the benefit of Doppler tracking of a landed probe in gaining knowledge of the interior structure of Mars. The precision Doppler measurements can determine the signature from planetary precession and nutation, especially when combined with historical data from previous Mars missions, to constrain the size and properties of the core. During the post-session discussion, the benefits of Doppler measurement gained from optical communications in measuring planetary winds was discussed, but acknowledged to be awaiting validation on a future planetary-entry-probe mission.

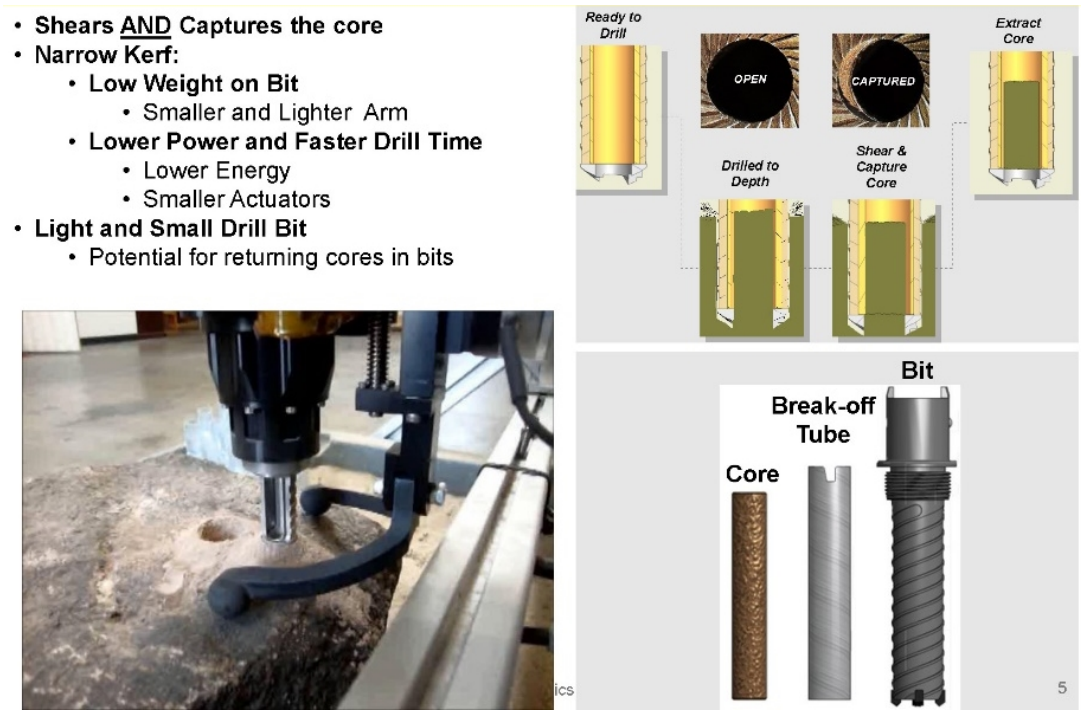

Figure 3-5. *Core breakoff and retention concept for the Mars 2020 rover [4].*

In their posters, Atkinson and Wayne presented techniques for investigating planetary winds. In keeping with the current focus on CubeSats and other small platforms for hosting science instrumentation, Castillo-Rogez's poster presented the case for these missions. Rafkin presented a concept for instrumentation on a future Mars mission, while Zacny's poster presented Honeybee's concepts for collecting and returning comet samples on future landed missions.

3.3 Findings

Planetary-entry-probe science is generated not only by science instrumentation, but also by the spacecraft subsystems and engineering instrumentation. Specific findings of the session are summarized below:

1. In general, radio science results are generated by analyzing propagation characteristics of radio signals broadcast by the spacecraft and/or entry-probe telecommunications equipment to return the science instrument data. This synergy between engineering and science is highly desirable since science data is generated "for free," without flying dedicated instrumentation.
2. Risk, perceived or real, is a constant in designing entry-probe missions. Resource margins, along with designs that leverage heritage systems, reduce risk consequences and likelihood of failure, but seldom completely eliminate the mission risk. Residual risk is an expected consequence of sending entry probes into environments that are not completely understood. In fact, if the environment were completely characterized, there would be little reason to conduct the entry-probe mission!

3. The single, overwhelming recommendation from this session was unanimous agreement that all future planetary-entry-probe missions be required to fly heatshield ablation sensors. There is a wealth of science and engineering to be gained from flying these sensors, at a low required financial and resource cost. Teams should be encouraged, if not required, to instrument heatshields for all future planetary-entry probes using flight-proven ablation sensors or other techniques as presented during the session.

4 Entry, Descent, and Landing (EDL) Technologies

By Aaron Morris[9] and Adarsh Rajguru[10]

This session was focused on the engineering and technology of end-to-end EDL architectures, including, landers, probes, and deployment of flight vehicles. Papers were presented in the fields of guidance, navigation, and control; hypersonic decelerators; architecture transitions; landing structures; and instrumentation. Instrumentation and algorithms associated with aerothermodynamic sensor systems, hazard detection and avoidance (HDA), and precision landing were also presented. Representatives from NASA, the European aerospace industry, the Japan Aerospace Exploration Agency (JAXA), and academia presented material and discussed approaches for advancing the state of the art in this field.

4.1 Introduction

NASA representatives presented summaries of MSL landing technology as applied to Mars 2020, inflatable hypersonic decelerators (Figure 4-1), mechanically deployed hypersonic decelerators (Figure 4-1), Mars EDL instrumentation (Figure 4-2), and EDL technology investments. European representatives discussed recent advances in parachute modeling and testing. A senior engineer from JAXA presented a summary of the Hayabusa vehicle design and testing. Three student presentations in this session discussed advances in hazard-avoidance algorithms and landing structures. Risk–reward balance, technology portfolio balance, and hazard avoidance were key topics discussed during the session.

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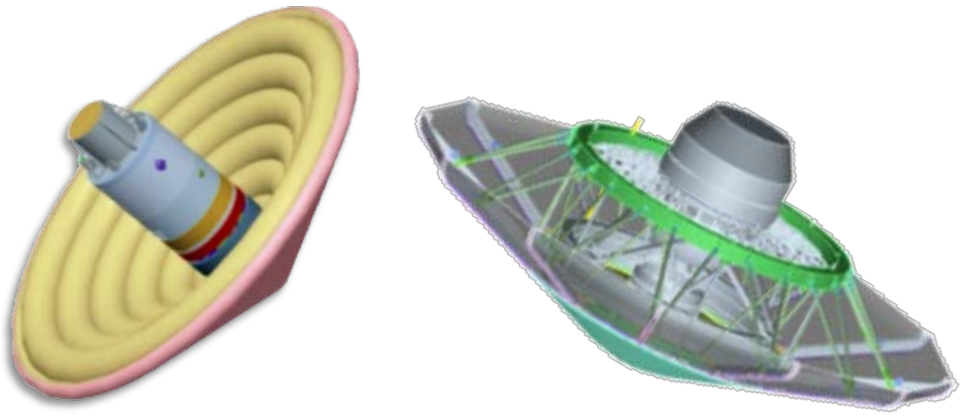

Figure 4-1. *Graphical representations of inflatable (left) and mechanically deployed (right) hypersonic decelerator concepts for planetary and Earth landing.*

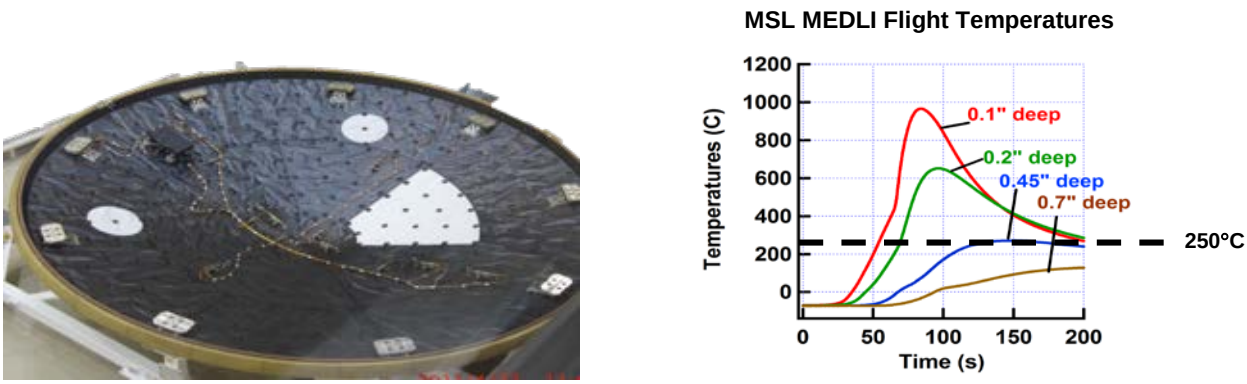

Figure 4-2. *Data gathered successfully from MSL EDL instrumentation package.*

4.2 Summary of Presentations and Posters

The introductory presentations are summarized here to provide some context for the discussion at the end of the session. Al Chen's status of the Mars 2020 EDL approach highlighted the differences and improvements from MSL to Mars 2020. The 2020 opportunity occurs at a more favorable point in the pressure cycle compared to MSL, resulting in greater altitude, propellant, and timeline margin during EDL. Specific issues from the MSL EDL sequence will be addressed on the next large lander, including a gravity anomaly and "sandy radar" phenomenon that led to off-nominal touchdown conditions. In addition, the Mars Descent Imager (MARDI) camera showed ice and volatiles deposited on the inside of the aeroshell upon release, so the outgassing properties of the spacecraft materials will likely be closely monitored for Mars 2020. The Mars EDL Instrument (MEDLI) suite is again baselined on Mars 2020, with improvements that include a backshell pressure measurement and several backshell thermal measurements (later detailed in Deepak Bose's talk). Other possible additions to Mars 2020 include a range trigger to reduce the landing footprint by 50%, terrain-relative navigation (TRN) to improve the likelihood of safe landing. The use of a new ringsail parachute, developed by the LDSD project, is unlikely at this time, but it could be employed if the mission requires additional parachute performance later in

its development. There are currently 27 candidate landing sites; the next site selection workshop is planned for June 2015, when the number of candidate sites will be reduced to eight.

Michelle Munk's presentation provided a top-level survey of the EDL content across NASA's Space Technology Mission Directorate (STMD). Initially Principal Investigators (now called Principal Technologists) within STMD seek and advocate for new content only within the Game Changing Development Program, but recently they have been elevated to guide technology investments across all nine STMD programs. This expanded role creates more opportunities to identify partnerships, use different procurement strategies, and influence technology maturation across a wider range of TRLs. EDL is one of the eight thrust areas within STMD, implying a sustained commitment to a continuous investment in this area. At the time of the workshop, there were approved EDL projects in seven of the nine STMD programs. Multiple EDL technology investments target science missions, as well as human Mars exploration. Significant strides have been made in EDL instrumentation during the past year: MEDLI data analysis was completed; Mars 2020 instrumentation was approved; the NASA Technology Executive Council signed a memo committing to consider instrumentation on all future EDL missions; and for the first time, the Discovery Announcement of Opportunity required EDL instrumentation. STMD is making significant investments in EDL, leveraging partnerships and opportunities to make progress in a limited-budget environment.

Posters ranged from updates on ongoing TPS developments—including conformal ablative materials, the ExoMars heatshield material, and the AVCOAT TPS for Orion—to more exotic materials, in situ energy generation, new landing concepts, and analysis capabilities. Of particular note was Julie Foster's poster, asking, "Where's Your EDL Data?" This was the community's annual reminder to contribute to and use the EDL Repository, a Web site dedicated to archiving EDL test and flight data, analysis results, and publications in a central location. This resource is supported by NASA's Office of the Chief Engineer to provide continuity and support engineering capability.

4.3 Discussion Points

While EDL technologies in a variety of configurations and levels of maturity were presented, two topics spurred the majority of discussions among participants. Discussions centered on those topics are summarized below.

Discussion #1: Hazard Detection and Avoidance

Svenja Woicke (PhD candidate, Delft University) offered a presentation related to her dissertation on hazard-avoidance algorithms (see also Figure 4-3). Her conclusion slide asserted that hazard-avoidance development is essential for planetary exploration. This was the subject of debate. The utility of HDA algorithms was questioned, particularly for Mars landings. The topic was hotly contested, with advocates for other destinations, such as Venus, stating that hazard avoidance is more important for destinations that are not as thoroughly mapped and observed as Mars.

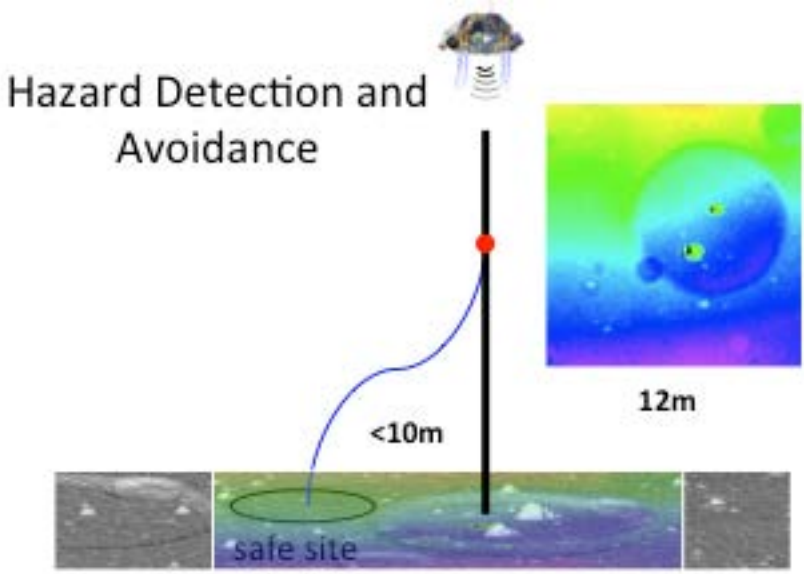

Figure 4-3. *Artist's representation of hazard detection and avoidance.*

Engineers involved with Mars 2020 pointed out that since hazards can be seen from Mars orbit, HDA might not be as useful as it would have been on previous Mars missions. One caveat is that HDA might be potentially beneficial if the useful range were extended 100–250 m. It was noted that HDA and precision landing are two distinct functions. Precision landing, with a focus on reducing the size of the landing ellipse, remains a valid goal for Mars. Mars landing engineers noted that a digital imagery map generated from high-definition images would allow for a pre-programmed hazards map.

Engineers associated with Venus landers observed that scientifically interesting landing sites on Venus are inherently hazardous. Further, Venus scientists and engineers suffer from a lack of high-resolution images, which are available to the Mars community. The proponents of HDA concluded that elegant, high-speed algorithms can pay dividends for the goal of improving HDA for poorly-mapped solid-body destinations.

It is obvious from the number of related posters and presentations, as well as the lively discussion, that this area will continue to see much interest within the community and may result in an upcoming EDL technology infusion within NASA.

Discussion #2: NASA EDL Technology Investments

Michelle Munk's presentation led to a discussion regarding the proper balance between risk and reward in these investments. Many participants mentioned examples of how project risk avoidance is leading to less innovative and more constrained missions. Session participants again reached a consensus that NASA and ESA must revisit the current paradigm of accepted technology risk.

There was additional discussion about the proper balance of investments across the TRL range. The need to push high-TRL technologies to final infusion was discussed, since projects are reluctant to adopt new technologies on their own initiative. However, the last push to infusion is

often the most expensive period of maturation, so few of these activities can be pursued under a limited budget. One method for ensuring that technologies can be infused on robotic science missions is to incentivize their use; NASA has done this on the last two Discovery mission solicitations. If the incentivized technologies were proposed, NASA offered an increase to the mission cost cap and guaranteed that the technologies would be matured with sufficient funding and on the appropriate schedule to be used on the mission. In addition, proposal review panels were instructed not to comment on the maturation risk of these externally-provided technologies.

4.4 Findings

The workshop discussion led to four recommendations and observations for consideration by NASA, ESA, and the aerospace industry:

1. The NASA Space Technology Mission Directorate (STMD) and other technology-development organizations should become more involved with universities. Students operate in low-budget environments, and hardware development in universities can be a challenge. However, low-TRL design and testing can be conducted efficiently and cost-effectively in a university environment. Low-risk technology is not necessarily tied to the least costly solution. As an example, CubeSats emerged from universities and were then infused into NASA and the aerospace market.
2. Objective system analyses must be conducted to compare and contrast EDL technologies. Analysis can elucidate effective solutions for the EDL phase of flight. The analysis can be used to prioritize the technical benefits and investments. Some EDL technologies are applicable only to human-scale Mars missions and not necessarily for use on robotic planetary missions, so understanding scalability is key.
3. Further work is needed to close the gaps in perception between technology developers and competitive mission proposal teams. Proposal teams form years prior to Announcements of Opportunity. Institutions expend considerable resources on proposal generation, so they must have confidence in the technologies to be willing to include them in their proposed concepts. This confidence is gained over time, with technology developers providing objective assessments of benefits and impacts to specific mission applications.

5 Inflatables and Deployables

By H.S. Griebel[11], J. Nott[12], T. Fisher[13], and R. Diaz-Silva[14]

The focus of this session was the science and technology behind all structures requiring inflation or deployment, whether they are intended for deployment in space, during atmospheric descent, or on the ground. Papers discussing the design, testing, and flight evaluation of deployment technologies and their specific thermodynamic and aerodynamic challenges, including material science challenges, were encouraged for submission, as well as papers related to packaging, manufacturing, and fabric/film processing and handling. Historically, this IPPW session has been an important venue for discussion of inflatable aerodynamic decelerators, both hypersonic and supersonic, from their concept formulation to flight-test results. Status updates in the development of inflatable and deployable hypersonic structures were highlighted during IPPW-11.

5.1 Introduction

Inflatable and rigid deployable mission components have been under research since the 1960s, but with the exception of the Vega Balloons and Earth-flight demonstrations, they have not been incorporated on crewed or robotic entry missions. Conventional rigid blunt-body entry vehicles continue to be used due to design heritage, resulting in high TRLs. While inflatable technology has been available for many years, progress is being made on advancing the maturity levels of supersonic and hypersonic inflatable aerodynamic decelerators, also known as supersonic inflatable aerodynamic decelerators (SIADs) and hypersonic inflatable aerodynamic decelerators (HIADs), respectively. Work under the LDSD program aims to flight-demonstrate 6- and 8-meter-diameter SIADs in addition to a new 30.5-meter Supersonic Disk Sail (SSDS) parachute [5]. HIAD technology has advanced significantly thanks to the Inflatable Reentry Vehicle Experiment (IRVE) missions with ongoing work to augment the testing envelope with new flight demonstrations. Here we find the High-Energy Atmospheric Reentry Test (HEART) and Terrestrial HIAD Orbital Reentry (THOR) concepts [6].

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Deployable concepts are also maturing and benefiting from advancements in and availability of flexible materials that can withstand the high aerodynamic and aerothermal loads experienced during atmospheric entry. Material testing and test articles for the ADEPT deployable concept were presented [7].

5.2 Relevant Missions

Missions to Mars and Venus could benefit from increased development and use of inflatable and deployable technologies, either in the form of a high-mass primary payload or as secondary payloads. THOR technology can support an entry mass of 315 kg, but potential Mars Precursor missions, with an 8- to 12-m-diameter inflatable aeroshell, launched from the International Space Station (ISS), could land a crewed 4500- to 6500-kg payload.

These technologies are key enablers when considering the geometric limitations imposed by existing launch vehicles, excelling in providing mass- and volume-efficient solutions to atmospheric entry [7]. By fitting inside a payload fairing in their stowed configuration, both ADEPT and HIAD could support a heatshield diameter larger than that enabled by a rigid structure. The heatshield is deployed prior to entry, with the larger drag area resulting in a lower ballistic coefficient. Advantages of this design include reductions in the maximum heating rate, total heat load, and deceleration loads experienced by the spacecraft [8].

Another concept presented was the NGAS and L'Garde VAMP. The VAMP concept would provide a long-lived (months to years), ultra-low-ballistic-coefficient semibuoyant aircraft vehicle that deploys prior to entering the Venus atmosphere, enters without an aeroshell, and carries science payloads to explore the upper atmosphere of Venus [9].

Recent advances have enabled smaller spacecraft, resulting in a significant growth in the number of flight opportunities. The emerging field of small-spacecraft development is developing novel applications for deployable entry vehicles as secondary payloads. Here the storable characteristic of deployable structures contributes significantly to minimizing interference with the primary payload in order to ease accommodation. Smith et al. highlighted the "high-value proposition of small spacecraft for frequent, incremental technology development and science return rather than the traditional high-cost and infrequent big-bang approaches" [6]. Smaller spacecraft flying as secondary payloads can now survive atmospheric entry thanks to the enabling characteristics of inflatable and deployable structures. Mission studies are underway for Mars and Venus [10] and Earth entry demonstrations [11]. Inflatable and deployable structures can be scaled for different missions. This scaling is exemplified in examples of the proposed use of ADEPT for a 15- to 23-meter crewed Mars mission, a 6-meter Venus mission, and a 1-meter nano/secondary-payload Mars mission [12].

5.3 State of the Art

5.3.1 *HIAD*

HIAD development was advanced by the IRVE missions. The last of these, IRVE-3, launched in July 2012. This suborbital rocket payload achieved a 469-km apogee, experiencing deceleration

forces up 20 Gs and a 15-W/cm^2 peak flux during reentry. The return payload inflated in space to a 3-m-diameter, 20-psi-internal-pressure stacked toroid covered with a TPS fabric, demonstrating survival in the reentry heating environment.

Follow-on work on HIAD features ground tests and flight demonstrations. During IPPW-11, work was presented describing a prototype 6-meter-diameter HIAD with an integrated, flexible TPS. This system was subjected to a static-load test series to verify the design's structural performance [7]. Such tests are key in evaluating the structure to ensure that it performs under flight-like conditions. As with its predecessors, the HIAD structure was constructed in a stacked toroid configuration. The outer layers are Nextel; inner layers are Aerogel felt and carbon felt for insulation; and the inner layer is a polyimide/aramid gas barrier. Figure 5-1 depicts the 6-meter HIAD with TPS and the vacuum membrane exerting a static loading pressure. The authors describe the test as follows: "Using an impermeable membrane seal draped over the test article, partial vacuum was pulled beneath the HIAD, resulting in a uniform static pressure load applied to the outer surface. During the test series an extensive amount of instrumentation was used to provide many data sets including: deformed shape, shoulder deflection, strap loads, cord loads, inflation pressures, and applied static load." These results feed into the development of the THOR article discussed next.

Figure 5-1. *6-meter HIAD with TPS (top), under 50,000 lb. of static load (bottom). These tests were performed at multiple inflation pressures.*

A proposed flight demonstration of a large-diameter HIAD is named the High-Energy Atmospheric Reentry Test, or HEART. But before that test, the THOR mission is planned. This mission is slated to fly in 2016 as a secondary payload on an Orbital Sciences commercial resupply mission to the ISS. THOR will launch with its HIAD stowed in a small cylinder between the Castor XL second-stage motor and the payload fairing of the Antares rocket. A key feature of this test is an atmospheric entry of 7.8 km/s, which will subject the HIAD to a 4-minute heating pulse with a maximum flux in the 40- to 50-W/cm^2 range. This is a much higher energy than that experienced in previous suborbital tests. THOR's HIAD will be 3.7 meters in diameter [11].

5.3.2 *ADEPT Concept*

The ADEPT concept features a mechanically deployed umbrella-like structure consisting of ribs, struts, and a flexible fabric cover. Together they form an aerodynamic decelerator capable of undergoing hypersonic flight for planetary entry [10]. A key feature in ADEPT's design is its heatshield, consisting of a cover skin manufactured with 3-D woven carbon cloth. The skin structure serves both as a TPS and as a structural surface that transfers aerodynamic forces to the underlying rib support structure. ADEPT has been under development at NASA since 2011 [10]. An architecture using ADEPT would benefit from a 10× reduction in G-load, a 25% reduction in flight-system mass, and a 10× reduction in peak heating rates [8].

Deployment of the umbrella-like structure was identified as a potential risk area. In order to reduce the uncertainty and gain experience, a 2-meter-diameter ground-test article (GTA) (Figure 5-2) was constructed. The GTA underwent a series of deployment tests to demonstrate the mechanical functionality of the technology and to further its development. These are key steps ahead of any flight opportunities. Yount et al. reported successful and informative tests demonstrating that the ADEPT configuration was feasible and reliable, its assembly procedure successful, and the system robust to the applied off-nominal conditions [8].

Figure 5-2. *ADEPT GTA shown deployed.*

Ground testing has also subjected the carbon woven fabric of ADEPT's skin to the extreme temperatures of expected entry conditions at Mars [12]. The design has already been tested in small-diameter Mars entry mission conditions (100-W/cm^2 and 100-lbf/inch^2 peaks), and testing is progressing for a 6-meter-diameter Venus mission. The carbon-thread-stitched seams that are crucial to the flexible cover were subjected to arc jet testing and tensile loading at NASA's ARC, as seen in Figure 5-3. This testing demonstrated that potential creep issues of the seam joined to carbon fabric were of no consequence. The carbon stitching did not fail, demonstrating a robustness that constitutes a breakthrough in the development and fielding of ADEPT.

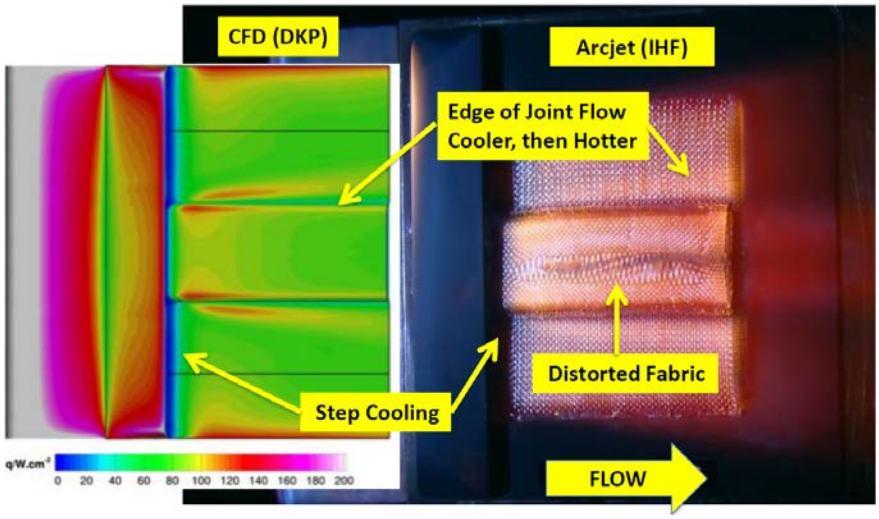

Figure 5-3. *Arc jet testing of woven carbon fabric joints.*

As described previously, the ADEPT concept has also been proposed as a heatshield for secondary payloads [10]. Among the key challenges that must be solved, according to the authors, is the reliability of the decelerator to achieve the desired shape using simple passive mechanical actuators (such as springs) that do not require power for deployment from the primary payload. The researchers presented their efforts in building a prototype that can be used to evaluate the functionality and reliability of the deployment mechanism. Low-speed wind-tunnel testing is planned as a follow-on for this prototype, enabling the evaluation of load-carrying capability and deflected shape. These activities are funded by NASA ARC's Innovation Fund. Pending STMD budget approvals, relevant-scale arc jet and sounding-rocket flight-testing is also expected.

5.4 Findings

This session highlighted much progress in maturing technologies to support future missions to Mars, Venus, and Titan. Inflatables have the potential to enable entirely new and innovative mission concepts, both as primary missions and as secondary payloads. Multiple modeling, use of a commercial code to simulate fluid-structure interaction, and test advances presented in this session in particular will aid in risk reduction. Specific findings during the session were as follows:

1. Inflatable heatshields have matured to the point where they can be demonstrated to be cost-efficient, safe, and reliable. While not currently flight-proven, inflatables are characterized by simple, reliable deployment scenarios. The substantial benefits afforded by inflatable and deployable space structures will be available to even the most conservative mission designer if the technology maturation programs proceed.
2. Entry requirements are the driver for specifying unique entry-system designs. Flight-proven, rigid aeroshells have satisfied these requirements to date precluding the use of inflatable and deployable technology on missions thus far. However, when entry requirements can no longer be satisfied by rigid aeroshells, inflatables and deployables will be speedily adopted. An example of entry requirements as a design driver occurred on

the MSL mission, where the Sky Crane technology, with no flight heritage, was approved for flight following an extensive process of design reviews and evaluation.

3. Developments in woven carbon materials enabling a reliable, flexible, ablatable TPS are applicable to both inflatable and deployable aeroshells [12] and have had a profound impact on their feasibility. Extensive ground tests for inflatable (HIAD) and deployable (ADEPT) systems are supporting the continual technology maturation [7], [8].
4. Deployable and inflatable vehicles implemented as secondary payloads can advance the technology and in some cases do useful science at Earth, Mars and Venus. Both HIAD and ADEPT technological capabilities for small science payloads stem from their ability to stow within a slender volume and deploy passively to achieve a mass-efficient drag surface with a high heat-rate capability.

6 Sustained Flight

By Jim Cutts[15], Jean-Pierre Lebreton[16], and Kim Reh[15]

This session included creative technical ideas and revolutionary concepts with the potential to enable the achievement of high-priority science. Key technical accomplishments during the last year included flight-demonstration of a tethered rotorcraft at Mars atmospheric density, demonstration that helium balloons could fly for many years at Titan without losing helium through diffusion, and progress in miniaturizing the guidance systems for fixed- and rotary-winged vehicles for Mars, Venus, and Titan. Concepts included a targeted Venus glider that could obtain visual images of the surface, a balloon mission that could make seismology measurements at Venus, and a technique of lift-gas compression (LGC) for balloon altitude control that could enable investigation of the Venus upper cloud layer. The LGC technique is also applicable to Titan and could enable a long-duration Titan mission with the ability to make repetitive, highly controllable descents to the surface.

6.1 Introduction

The purpose of this session was to review key developments in the state-of-the-art technologies during the last year, and to identify opportunities for future development and application. The session encompassed flight with lighter-than-atmosphere (LTA) and heavier-than-atmosphere (HTA) vehicles and included two missions in which these capabilities could be used effectively in concert with one another. The application of emerging technology in planetary exploration was a key consideration of all papers presented.

6.2 Relevant Missions

There is growing interest in the use of sustained flight for scientific exploration of bodies in the solar system with significant atmospheres and solid surfaces with complex and diverse geology. Venus, with the densest atmosphere of all and the only planet so far to have been explored in this way, continues as a prime object of interest. Mars, with its tenuous atmosphere, presents

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significant challenges, but new developments promise to overcome these. Finally, Saturn's moon Titan, whose atmosphere is closest in density to that of the Earth, offers a rich set of opportunities for exploration by both LTA and HTA vehicles. The following innovative applications of sustained-flight technologies are discussed in the paragraphs below:

- Fixed- and rotary-winged flight at Mars, Venus, and Titan
- Mars rotorcraft
- Titan long-duration balloons
- Titan Aerial Daughtercraft
- Altitude-controlled balloons for long-duration flights at Venus
- Venus seismology from a balloon
- Venus glider
- Future Titan exploration

6.3 State of the Art

Aerial platforms can enable new opportunities in planetary science and exploration missions. IPPW-11 showcased an array of impressive advances in technologies and techniques that enable sustained flight at planetary bodies with atmospheres. Advances in state-of-the-art that were addressed are described below.

6.3.1 *Fixed- and Rotary-Winged Flight Concepts at Mars, Venus, and Titan*

A foundation for discussion of HTA vehicles was established in an invited paper by Phil Tokamaru of AeroVironment [14]. This company, a leader in innovative robotic aerial vehicles for Earth, is applying its expertise to enable flight at Mars, Venus, and Titan. Tokamaru compared the key parameters governing flight with fixed- and rotary-winged vehicles and described the aerodynamic trades for three concepts: a Venus glider, a Mars rotorcraft, and a Venus rotorcraft. These three concepts were also the subject of later presentations dealing with scientific objectives, guidance and control issues, thermal control, and flight-test results. For Venus and Titan, with their dense atmospheres, margins are large, and non-aerodynamical factors such as the extreme temperature ranges of operation become the primary design drivers. For flight at Mars, on the other hand, margins are small, and payload mass and lifetime are the primary design drivers.

6.3.2 *Mars Rotorcraft Concept*

A prototype rotorcraft capable of flight in the tenuous atmosphere of Mars has been designed at JPL and tested at Mars atmospheric density [15]. The rotor is driven by an electric motor and rechargeable battery. The vehicle (see Figure 6-1) is designed for sorties of less than 15 minutes followed by battery recharge using solar energy.

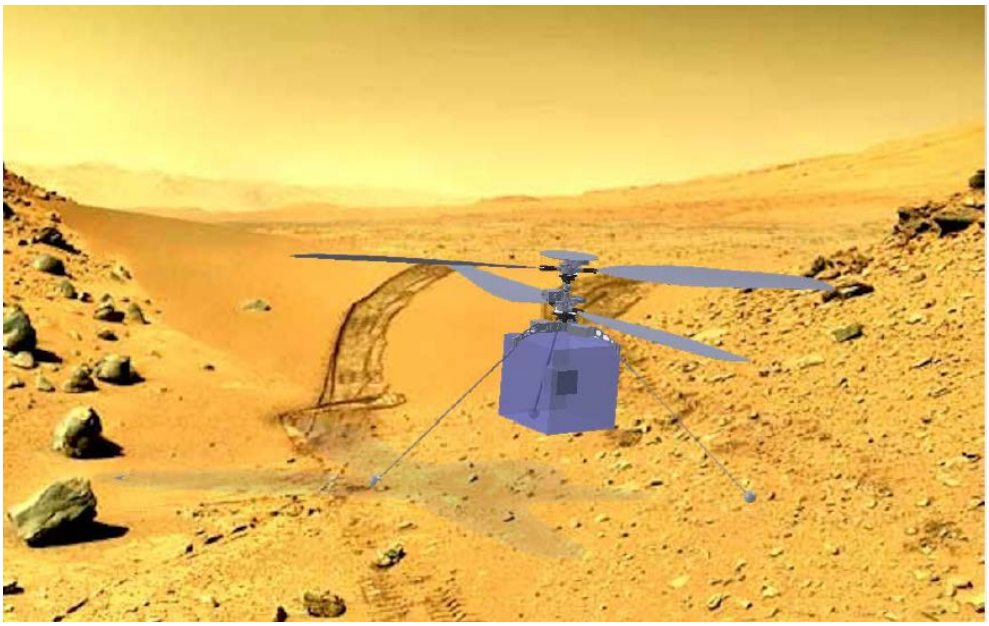

***Figure 6-1**. The Mars rotorcraft is designed to make short excursions to image terrain and plan a rover traverse.*

This concept could serve in a critical support role for surface rovers. Mission planners for Spirit, Opportunity, and Curiosity rovers have experienced great difficulty in defining safe routes that prevent the rover from being trapped in soft sand or damaged by sharp rocks. The rotorcraft could provide higher-resolution surface images than are now possible from orbit to "scout" the path ahead. It could also image much greater areas than is possible with rover-mounted cameras. Finally, it could fly where rovers can't drive and potentially retrieve samples from those locations. If sterilized properly (for planetary protection), such a rotorcraft could potentially retrieve samples from special regions on Mars.

A rotor of diameter 0.7 m was designed and fabricated by AeroVironment for low Reynolds numbers (5700) in the thin Mars atmosphere and to be comfortably subsonic (Mach 0.5). In order to bracket the expected rotor performance as a function of Reynolds number, AeroVironment also conducted tests at two additional chamber pressures (~527 Pa and ~1055 Pa). Tethered flight was successfully demonstrated in a 10-m Mars simulation chamber.

6.3.3 *Titan Long-Duration Balloon Concept*

New laboratory testing of helium permeability in a balloon envelope for a conceptual Titan balloon have been conducted at Titan's environmental temperature of 78 K [16]. Permeability was determined to be four orders of magnitude below that at room temperature (Figure 6-2). This result indicates that diffusion through the envelope would not be a significant limitation on the lifetime of a Titan balloon mission. It would enable Titan balloons to achieve lifetimes measured in years, thereby increasing their scientific utility.

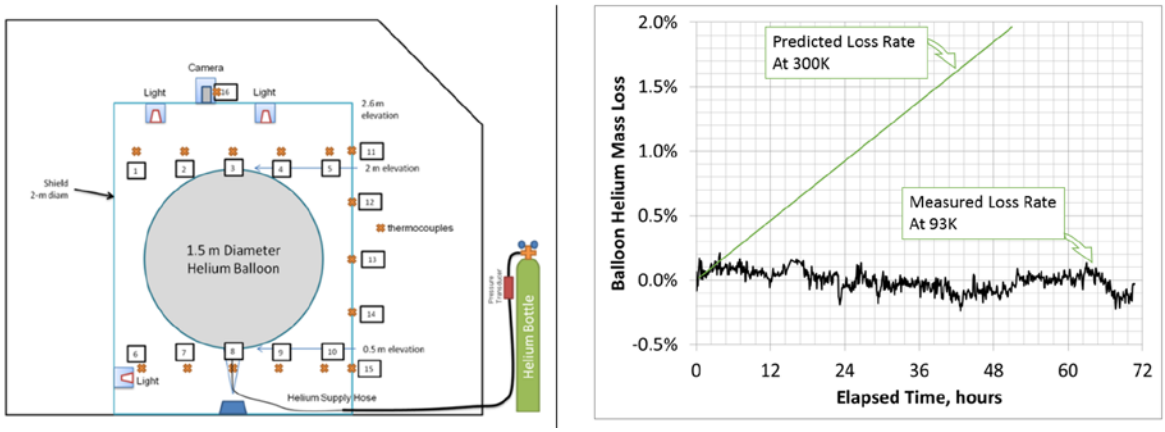

Figure 6-2. *Laboratory test of leakage of helium from a balloon at Titan temperatures (left) confirms that the leakage rate due to diffusion is four orders of magnitude below that at room temperature.*

6.3.4 *Titan Aerial Daughtercraft Concept*

In contrast with Mars, where flight is difficult and payload fractions are tiny, the dense atmosphere and low gravity of Titan make flight almost effortless and science opportunities abundant. The Titan Aerial Daughtercraft is envisaged as a rotorcraft that would retrieve samples and return them to a parent vehicle, which could be either a balloon gondola or a stationary lander (Figure 6-3).

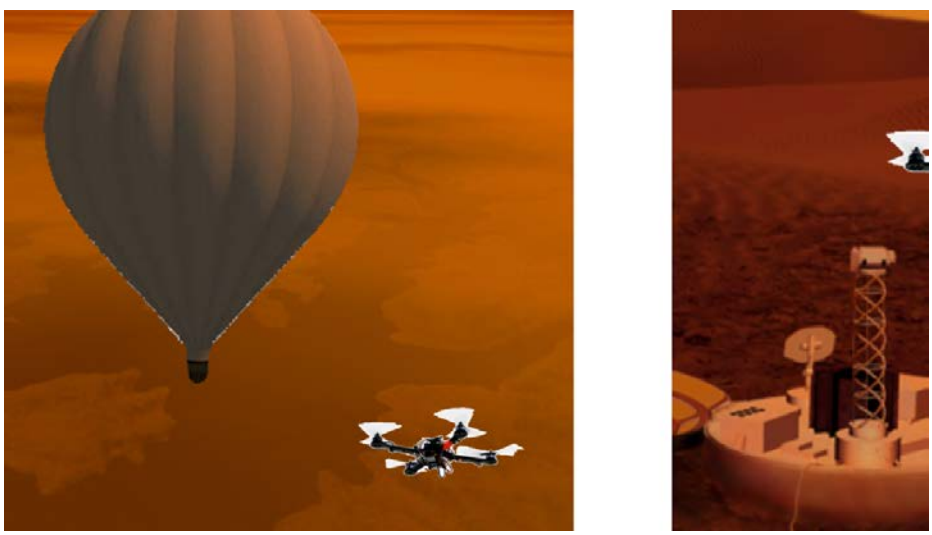

Figure 6-3. *Titan rotorcraft deployed from either a balloon (left) or a stationary lander (right).*

The autonomous navigation functions needed for flight at Titan essentially exist today. Because of the benign radiation environment at Titan, a result of shielding by the thick atmosphere, sensors and processors that are commercially available might suffice without the need for radiation-hardening. Components and mechanisms for operation in the extremely cold Titan environment appear attainable. The primary challenge is sampling and sample transfer, the focus of STMD NASA Innovative Advanced Concepts (NIAC) investments [17].

6.3.5 *Notional Altitude-Controlled Balloons for Long-Duration Flights at Venus*

In the context of developing an approach for investigating the upper cloud layer on Venus (60 to 80 km altitude), two approaches to an altitude-controlled balloon were investigated by Paul Voss [18]: lift-gas compression (LGC) and ambient-gas compression (AGC) (Figure 6-4). Both can be implemented using a conventional super-pressure balloon, such as that flown on the Soviet Vega mission in the 1980s, and Venus Aerostatic-Lift Observatories for in Situ Research (VALOR) and European Venus Explorer (EVE), proposed to NASA and ESA competitive programs, respectively. For a 60-kg balloon system with a 20-kg payload, the LGC balloon concept requires half the pump power (25 W vs. 50 W) to perform altitude changes. The LGC balloon also avoids pumping ambient gas containing sulfur dioxide and acidic cloud particles. Small LGC balloons controlled remotely from the US have been used routinely over the last decade in scientific flights over Antarctica, Greenland, Brazil, and Mexico.

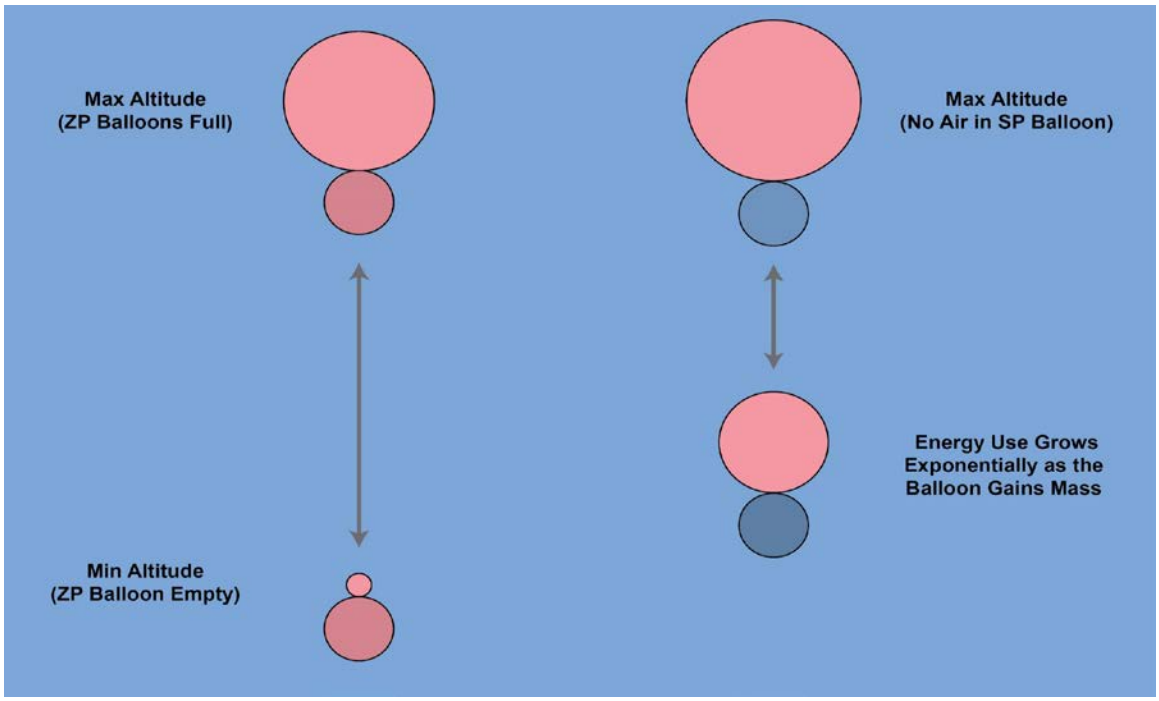

Figure 6-4. *Comparison of altitude control with lift-gas compression (LGC) balloon concept and ambient-gas compression balloon concept (right). Envelopes containing helium are shown in pink with ambient atmosphere in blue. "SP" denotes a super-pressure balloon; "ZP" denotes zero-pressure balloon.*

6.3.6 *Venus Seismology from a Balloon*

David Mimoun, of Institut Supérieur de l'Aéronautique et de l'Espace (ISAE) in Toulouse, described a new technique [19] for studying the interior of Venus from a Venus balloon platform by measuring infrasound signals caused by Venus quakes (Figure 6-5). Earthquakes also produce infrasound, but on Venus their intensity is much greater for a given-size quake because of the enhancement from the acoustic impedance match between the Venus surface and the dense atmosphere. The technique would require a constant-altitude balloon floating at an altitude near 54 km, where temperatures are comparatively benign and a long-duration seismic experiment is

practical. Since no Venus surface lander has operated for more than 3 hours, traditional surface seismometry is challenging at best.

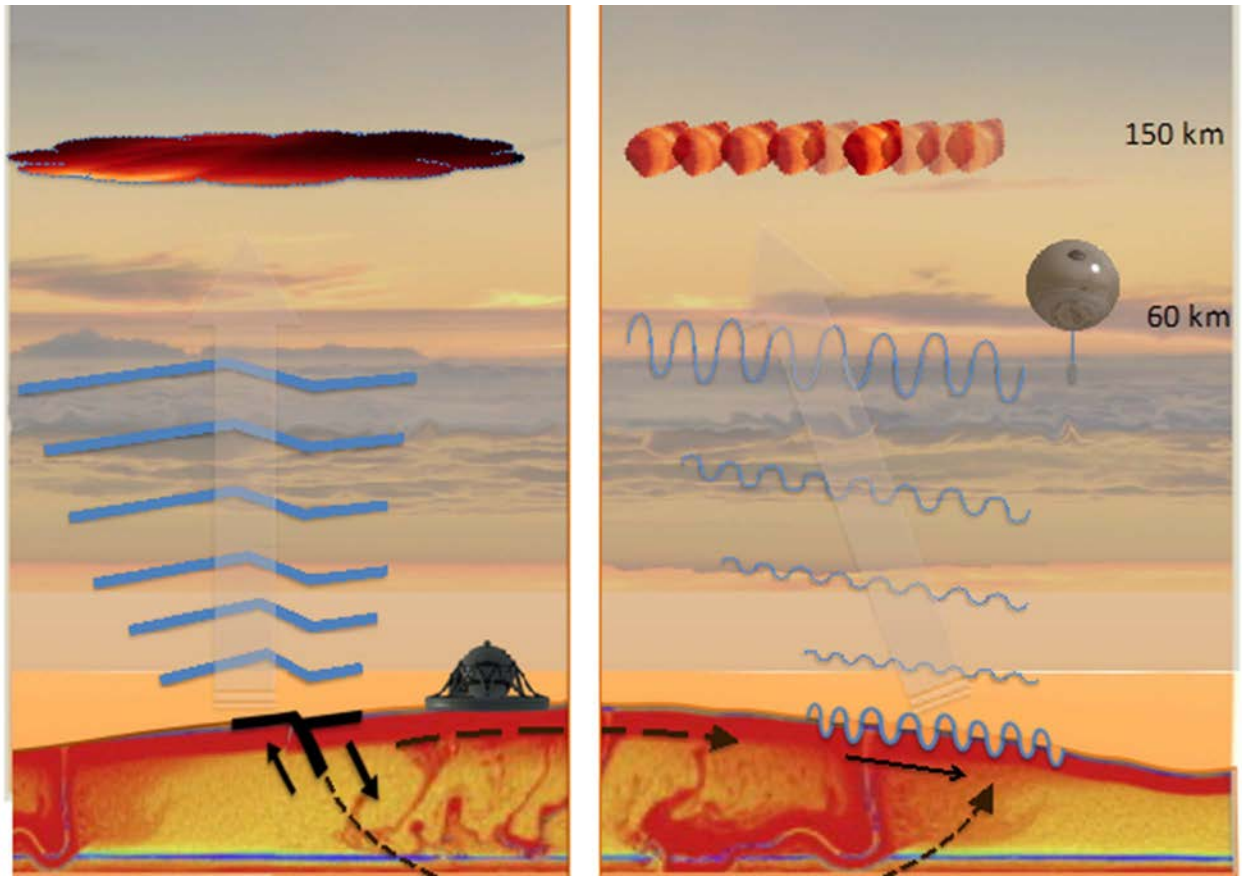

Figure 6-5. *Infrasound caused by Venus quakes can be observed from altitudes where temperatures are compatible with conventional electronics, in contrast with the surface, where the temperature is 460˚C. Infrasound might propagate directly upward from the source quake (left) or as a result of ground motions from a surface seismic wave (right), causing vertical motions at the surface (Rayleigh wave) at great distances from the source.*

6.3.7 *Venus Glider Concept*

The resolution gap, and hence the knowledge gap, between orbital imaging and imaging from a lander/rover is much larger for Venus than it is for Mars. The Venus glider concept (Figure 6-6) is designed to fill this gap [20].

The Venus glider would be deployed from a balloon and would initially glide ahead of the balloon before plunging rapidly to the near-surface region and levelling off to acquire stereoimaging coverage of a designated target. These images are generated at ranges from 3 km to the surface, where atmospheric backscatter and attenuation is reduced and where image quality is therefore expected to be very good. Since the initial point of deployment is well known, it could be navigated much more accurately to the surface than could a Venus lander entering from orbit. Key technologies for this concept are guidance, thermal control, and aerodynamic control.

Gliding can be sustained for at least as long as the temperature within the electronics can be maintained in an acceptable range within the high-temperature environment.

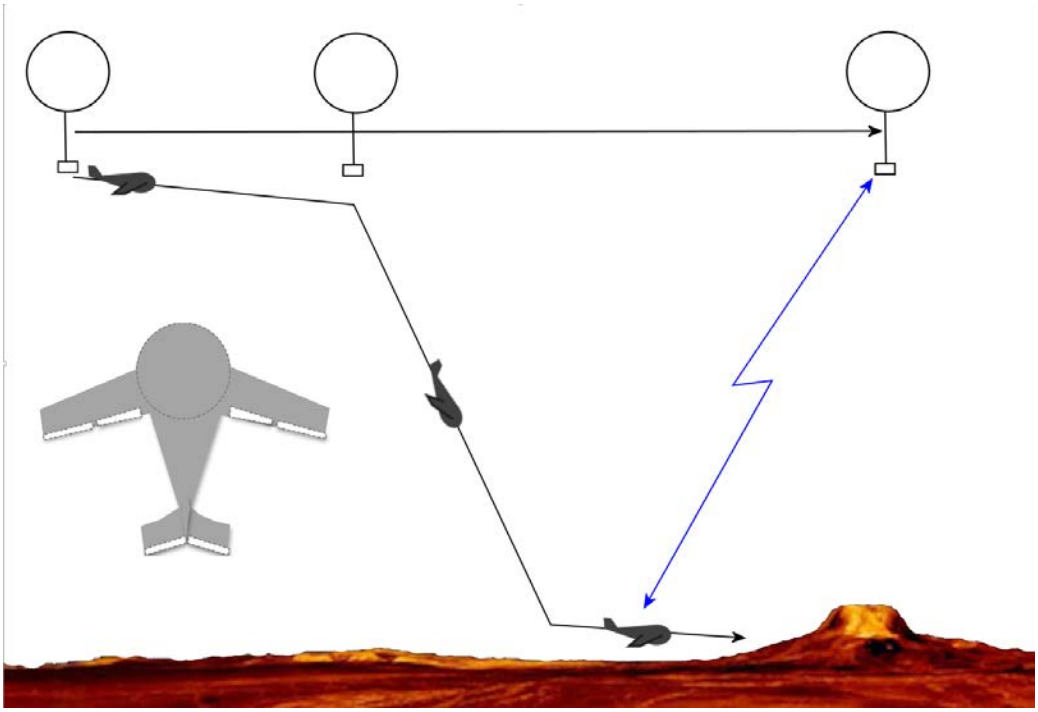

Figure 6-6. *The Venus glider concept would be targeted with high precision to candidate landing sites and carry out science and landing-site verification. Both the glider and the balloon from which it is deployed host imaging systems and use compact, state-of-the-art guidance.*

6.3.8 *Potential Future Titan Exploration*

Titan retains its attraction as an extraordinarily important science target for aerial exploration; both LTA (balloons) and HTA (rotorcraft) vehicle concepts would be feasible. They could be used in combination to exploit synergies between the long duration and global access of a Titan balloon and the surface-sample-acquisition capability of the rotorcraft.

The demonstration of ultralow helium loss in a Titan super-pressure balloon, reported in the paper by Pauken, supports the feasible operation of helium balloons with operating lifetimes of many years. The LGC technology could enable altitude control [5] for this balloon. In the benign Titan environment, with little diurnal variation in solar input, the amount of helium to be pumped, and hence the power requirements, are much lower than for Venus. Consequently, LGC would enable a balloon-borne rotorcraft to be deployed much closer to the Titan surface, increasing its payload capability.

A long-duration balloon with altitude control was a key element in the joint NASA-ESA Titan Saturn System Mission (TSSM) concept developed between 2007 and 2009. The TSSM mission concept included a Montgolfière balloon [21] containing ambient atmosphere heated with waste heat from a radioisotope power system (RPS). This required a very large envelope and a protracted deployment sequence. It offered slender payload margins and weak control

authority. With the two key technology developments described at IPPW-11 that address these problems, a Titan helium balloon has become a credible candidate for a robust, long-lived aerial mission with altitude control.

6.4 Opportunities and Future Development

There are several opportunities for potential application of the technologies described here and needs for future development.

1. Deployment of a notional Mars rotorcraft could enhance the science and facilitate path-planning for the Mars 2020 mission, which has a rover that will collect samples for potential future return. Opportunities might also exist with ESA's ExoMars.
2. Demonstration of Venus seismology techniques in a technology-demonstration mission would provide a proof-of-concept for reaching the sensitivity levels needed for a dedicated science mission.
3. Investment in sample-acquisition and sample-transfer technology would advance the maturity of a Titan (rotorcraft) daughter craft
4. Demonstration of the ability of pumps for LCD technology to operate at Titan temperatures could firmly establish the technology for balloon altitude-control at Titan.

6.5 Findings

The findings from the Sustained Flight session were as follows:

1. Adoption of aerial missions for planetary exploration requires that they provide unique science that cannot be accomplished in other ways and that the performance of the vehicles—specifically range, duration, and positional control—are adequate for accomplishing the science objectives. The continuing scientific productivity of vehicles like Cassini, Opportunity, and Curiosity has emphasized the value of a long-duration mission capability.
2. The Mars and Titan Rotorcraft concepts described in this session can do impressive science and are technically credible. In the case of Mars Rotorcraft, a very small vehicle on Mars 2020 could be deployed to the surface and provide repeated reconnaissance imaging around a rover for defining safe, scientifically productive traverses. Larger vehicles could be used for sample acquisition and retrieval at both Mars and Titan.
3. The LGC technique for balloon altitude control discussed for Venus is also applicable at Titan and represents an energy-efficient means of controlling altitude coupled with a practical way of making emergency ascents from near-surface hazards. It would allow vertical traverses to investigate changes in cloud conditions in the atmosphere and descent to, as well as sampling of, the surface.
4. Test results confirming a four-orders-of-magnitude reduction in the helium permeability of balloon materials at Titan temperatures could enable Titan aerial missions with lifetimes of many years. Coupling this development with the use of LGC techniques, helium balloons have now become a much more attractive option for Titan exploration

than the Titan Montgolfière balloon baselined for the proposed joint NASA-ESA Titan Saturn System Mission (TSSM) in 2008.

5. The concept for detecting seismic events on Venus using infrasound measurements from a balloon platform opens up an entirely new area of science. Given the impracticality of deploying long-term seismic stations in the searing heat of the surface at a temperature of 460°C, aerial systems could solve a long-standing exploration problem for the study of Venus.

7 Modeling, Simulation, and Testing

By Kerry Zarchi[17], Carlie Zumwalt[18], Christian Mundt[19], Benoit Pigneur[20], and Mike Pauken[21]

This session explored the state of the art and future direction of modeling, simulation, and testing (MS&T) in the planetary probe environment.

7.1 Introduction

MS&T aids in the design and analysis of missions. Without prediction methods such as these, the risk and cost of supporting science would be unreasonable, and assessment of risk and cost would rely purely on theoretical analysis. MS&T addresses a wide array of issues—from aerothermodynamics to quantum mechanics to landing systems. MS&T also provides verification and validation of engineering analyses, without which hefty and restricting margins would be required to ensure success.

The three elements of MS&T go hand in hand. Modeling and simulation can inform testing, and vice versa, to help reduce uncertainties and build confidence. At times they are in competition with each other. Since testing can be expensive and modeling cheap, with modeling often depending on excessive assumptions, many might choose to use only modeling and forego testing.

All three disciplines are needed in order to verify and validate their results against each other. Modeling and simulation can expose impurities in testing. Testing can reveal physical phenomena that were previously unknown.

7.2 Relevant Missions

Science missions to solar system destinations are greatly dependent upon MS&T. Because we cannot observe flight at another solar system body easily, we must use MS&T to extrapolate and

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predict environments at the target. Accurate prediction of performance informs the design of spacecraft and instruments. A recent example of the payoff for MS&T is the successful EDL of MSL and the subsequent deployment of the Curiosity rover by the entirely new Sky Crane. The successful arrival of Rosetta at comet 67P/Churyumov-Gerasimenko and the subsequent of its Philae lander, which occurred after IPPW-11, is another example of MS&T's role in support of a landed mission.

7.3 State of the Art

The state of the art in MS&T is heavily leveraged in nearly all aspects of current mission design. Reliance on modeling and simulation is growing because these are less costly and have a faster turnaround than does testing. However, the importance of testing should not be underestimated. Simulation is also essential in order to design testing, and to fully exploit testing results.

7.3.1 *Ballistic Probes and Hypervelocity Impactor Concepts*

One of the fundamental questions that planetary exploration seeks to address is whether there is evidence of life forms in our solar system in locations other than Earth. Since water is one of the key ingredients for life, there is considerable focus on Europa because it appears to have a liquid water ocean below a thick ice layer. Kohlman [22] at NASA Glenn Research Center investigated ballistic probes for penetrating ice at cryogenic temperatures. Computer simulations of the impact dynamics and penetration were developed, and results were presented on several projectile shapes. The simulations incorporated data collected from ballistic impact tests on ice at 100 K. Future work calls for testing at higher impact velocities and obtaining additional mechanical properties for ice that account for compositional variation, fracture rate mechanics, and friction properties. A photograph of a ballistic impact into cryogenic ice is shown in Figure 7-1.

Figure 7-1. *High-speed photograph of a ballistic impact on cryogenic ice.*

Hypervelocity impacts impart significant energy into materials, which might cause chemical decomposition of molecular species. Researchers at Caltech and JPL investigated the energetics and fragmentation effects on molecular species when they are subjected to velocity impacts from 14 to 17 km/s [23]. Data from the Cassini Ion and Neutral Mass Spectrometer collected

during flybys of Enceladus and Titan were analyzed using electron force-field and reactive force-field models to develop material- and geometry-related design parameters for the proposed Europa mission's mass spectrometer. The researchers benchmarked the physisorption, chemisorption, and fragmentation of H_2O, CO_2, and O_2—over a range of impact angles and velocities, on two candidate surfaces—to determine material and geometric design choices for the instrument's aperture.

7.3.2 *Entry, Descent, and Landing Systems*

MS&T of EDL systems covers the complete life cycle of landed missions from design concepts through reconstruction of actual landing event data. Buchwald [24] described how landing system design requires a combination of dynamic simulation models and the performance of relevant component- and system-level testing. Landing systems are composed of several components integrated within an overall architecture. Nonlinearity in component responses can make predictions of performance difficult when these responses are integrated into system-level models. Component modeling requires comparison of individual components tested in relevant environments and loads. Then the development of subsystem- and system-level models must have corresponding subsystem- and system-level tests for verification and validation.

In preparation for the 2016 ESA ExoMars mission, Van Hove and Karatekin [25] examined acceleration and gyroscope data from the 2008 Phoenix entry into the Mars atmosphere. Post-flight analysis of engineering data provided atmospheric profile reconstruction that can be used as an in situ science investigation of the Mars environment, and uncertainty analysis based on stochastic sampling and Bayesian state estimation revealed that uncertainty limits may be overestimated due to white noise in the data.

A feature that consistently drives landing site selection is the degree of landing hazards that must be avoided. Witte [26] presented an algorithm that permits evaluation of the terrain by a lander as it approaches the surface so that trajectory adjustments can be made to increase the probability of a successful landing by hazard avoidance. The HDA algorithm reads terrain maps of slopes, surface roughness, and shadows, as shown in Figure 7-2, to generate a landing map matrix that minimizes hazards. At present this tool is useful for mission planning purposes rather than real-time landing operations.

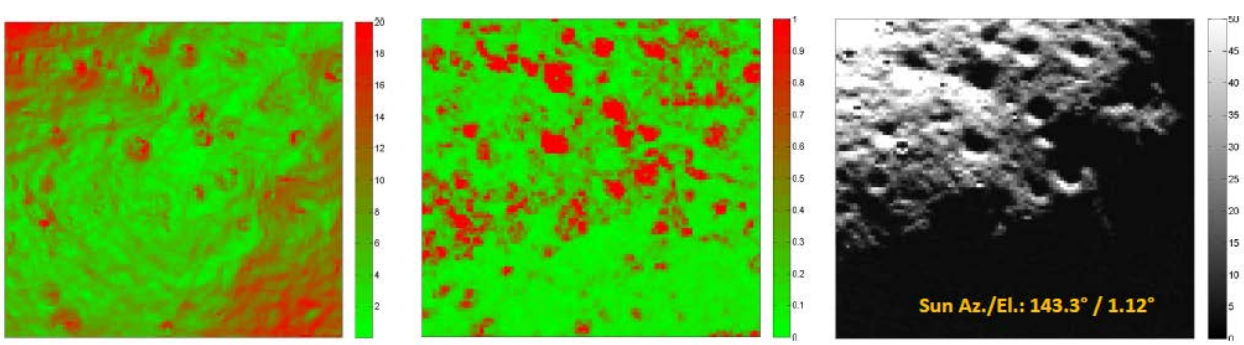

Figure 7-2. *High-resolution terrain-mapping of slope (left), roughness (middle), and shadows (right) used for generating hazard-detection-and-avoidance maps.*

Asteroids present perhaps the most challenging landing operations because of their very weak gravitational fields, loose regolith, and rock size distributions. There are very few flat surfaces observed on asteroids. Tardivel et al. [27] developed a surface-modeling system that incorporates faceted surface features on a 1-m scale or less, monolithic surfaces, and distributed rock fields, as shown in Figure 7-3. The landing analysis includes rock impacts during bounces, slides, and rolls. The surface model is used with a dynamic landing model to evaluate the effects of landing parameters such as deployment altitude, coefficient of restitution, and rolling resistance.

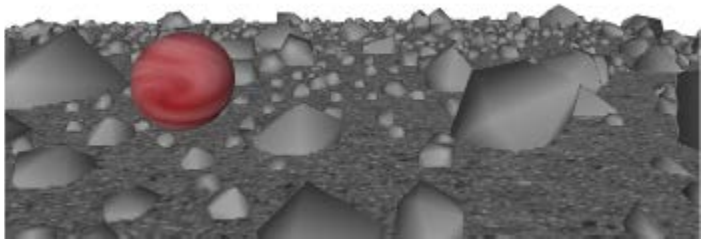

Figure 7-3. *Feature-rich surface model of an asteroid for evaluating landing performance.*

Landings that use a powered descent engine produce significant interactions with the surface that can result in problems for the landed vehicle either during the final moments of descent or afterwards due to the amount of dust, rocks, and debris redistributed. Sengupta et al. [28] developed an analytical model to predict erosion and deposition rates, crater geometry, and particulate trajectories during powered descent. Data from Viking, Phoenix, and Curiosity, such as that shown in Figure 7-4, were used to develop scaling relationships. This model offers vehicle designers information needed to provide adequate safeguards to reduce risk associated with landing a powered vehicle.

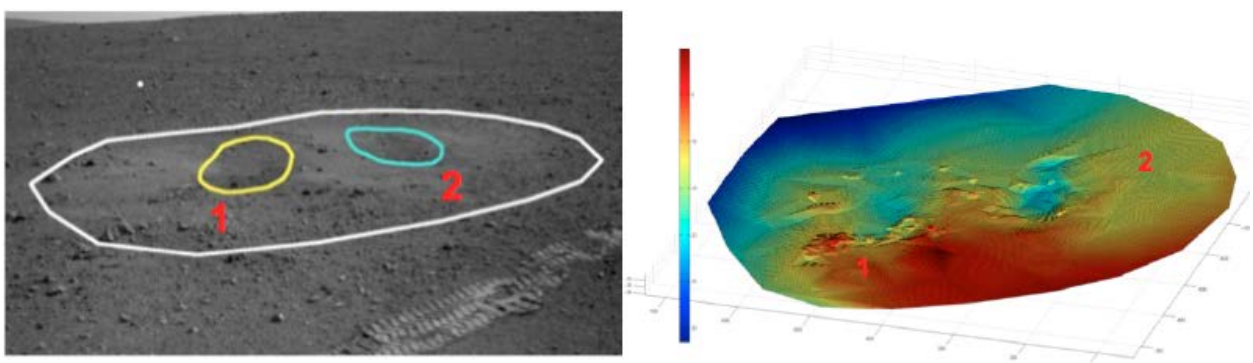

Figure 7-4*. Image processing of the eroded surface from the MSL landing site for evaluating plume impingement during descent.*

7.3.3 *Thermal Systems*

Thermal systems encompass a wide range of applications featuring an updated Uranus atmospheric model, expendable cooling for Venus landers, and testing of planetary-probe TPS materials in extreme entry environments.

Missions with probes descending into the atmospheres of Venus or the gas giants require new TPSs for their aeroshells. Gasch et al. [29] discussed arc jet and laser testing capabilities for simulating the high heat fluxes generated during atmospheric entry. The test programs typically evaluate samples on the order of 2.5 to 5 cm in diameter, as shown in Figure 7-5. Data collected from the heat-flux testing (from 1850 to 8000 W/cm^2) are used in extrapolating heatshield performance for various planets under atmospheric entry conditions.

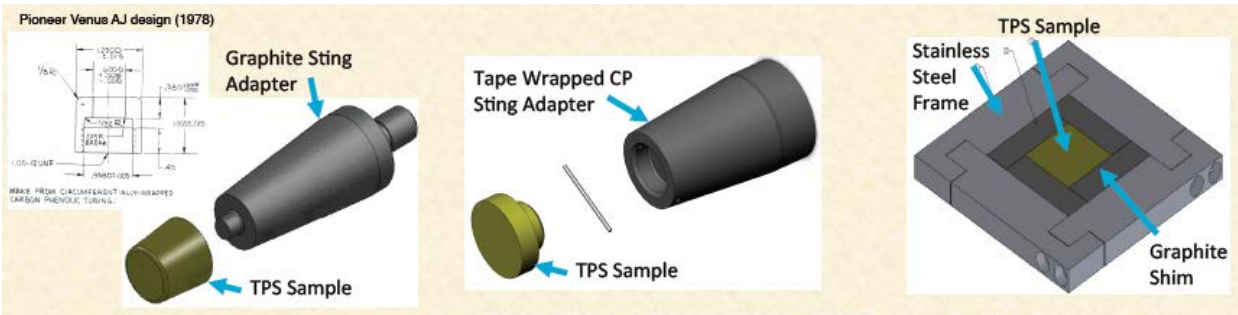

Figure 7-5. *Test sample configurations for arc jet testing (left and middle) and laser testing (right).*

Designing a probe to survive atmospheric entry requires an understanding of the temperature, pressure, and density atmospheric profiles. A notional Uranus probe mission must rely on data collected during the Voyager mission flyby in 1986 or fly a probe ahead of a future mission. Allen et al. [30] collected data from earlier publications on the lower and upper atmospheric properties and combined them into a unified model of the Uranus atmosphere, as shown in Figure 7-6.

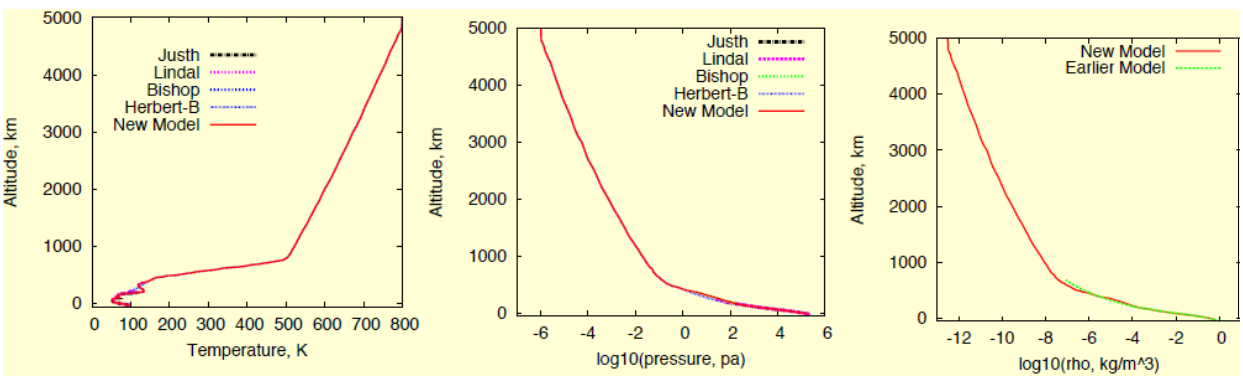

Figure 7-6. *Temperature, pressure, and density profiles for Uranus.*

A mission to the Venus surface requires surviving an extremely challenging environment at 460°C and 90 bars pressure. Previous Soviet landers operated for only a couple hours, with recent proposed missions confined to similar durations. Since we do not have high-temperature electronics and components that will survive in the Venus environment, Pauken et al. [31] described a method of expendable cooling using liquid ammonia as a coolant. This system removes internally generated heat from electronics and provides cooling of the pressure vessel wall to enable operating durations on the order of 16 to 24 hours. Surface missions of this duration may permit human in the loop interaction to select sampling systems science targets for. A heat-flow diagram of the analytical thermal model is shown in Figure 7-7.

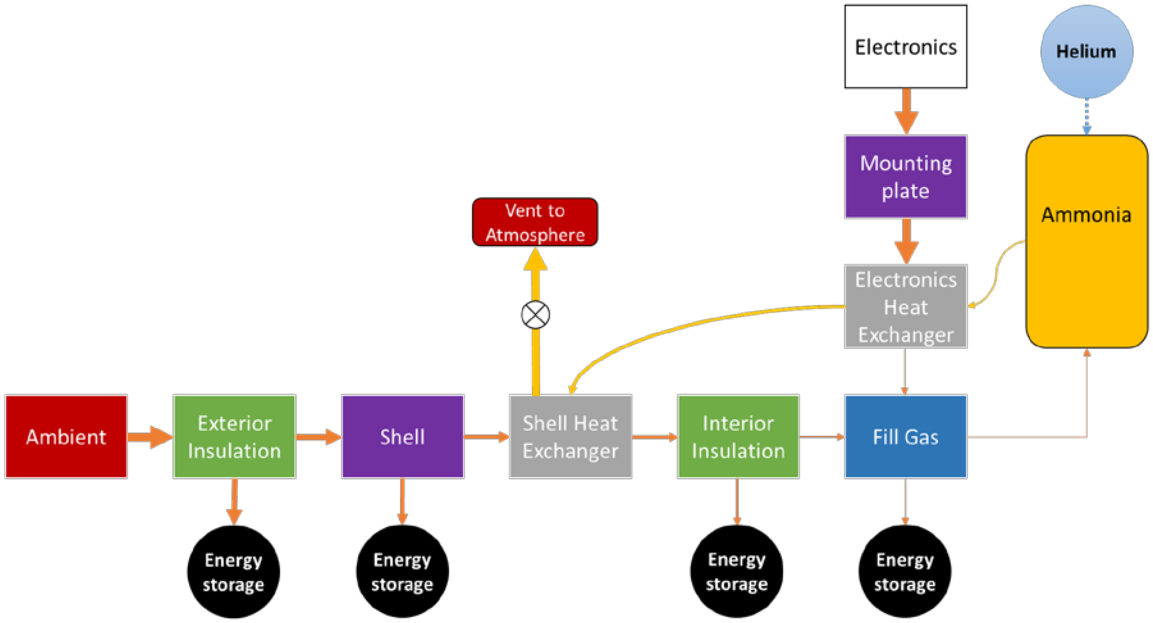

Figure 7-7. *Block diagram of an expendable ammonia cooling system for a Venus lander.*

7.3.4 *Structures*

Structural design of atmospheric entry vehicles must simultaneously satisfy constraints in aerodynamic loading, stability, volumetric and mass limits, and thermal survivability. Probe designs have relied on empirical testing to meet mission and system constraints. Developing parametric studies of all the major design parameters is a computationally intensive undertaking requiring significant resources and time to complete and analyze. Perino et al. [32] devised an automated process for performing parametric analysis of dynamic structure loads for entry-probe concepts. The analytical tool they developed permits geometric variation of cone angle and vehicle diameter, mass variation for the payload, and TPS and material property variations in elastic modulus and thickness. Parameters derived through this rapid, automated process define a larger trade space than do those obtained through empirical testing or historical precedent. Figure 7-8 shows parametric variations in a finite-element-model probe design using an automatic, rapid-build script process. The results of the parametric evaluation on designed vehicle mass are illustrated on the right side of the figure.

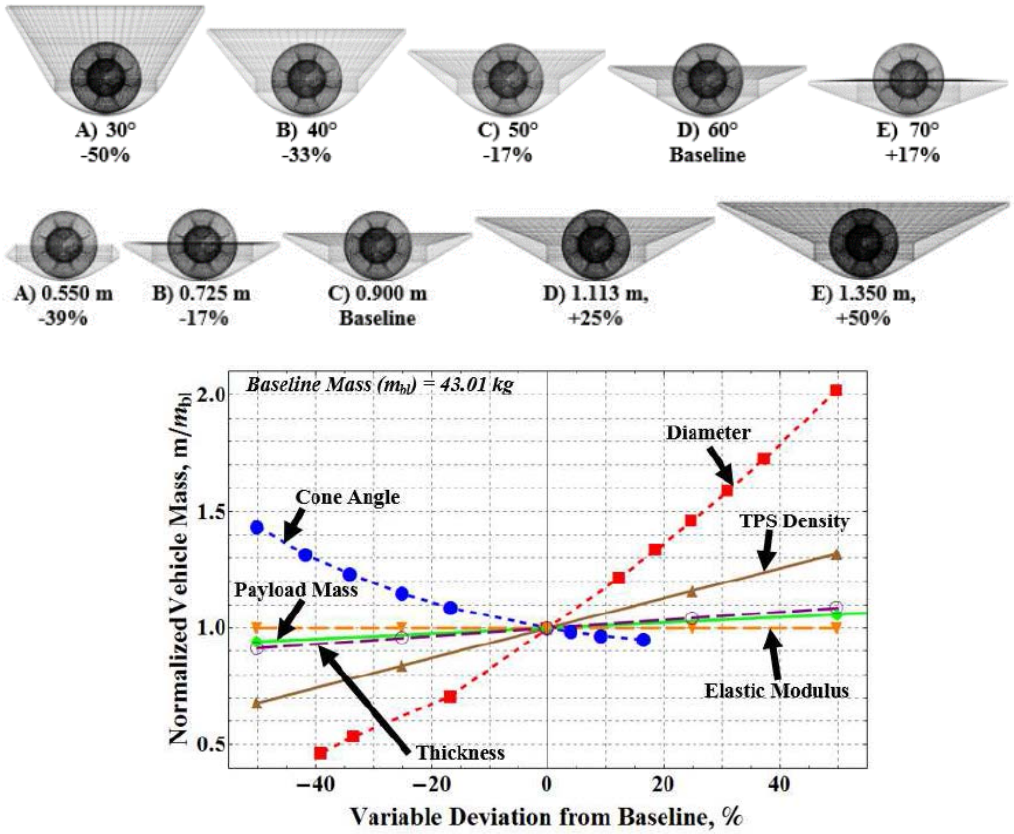

***Figure 7-8**. Parametric variation of entry-probe geometry and plot of relative mass effects over parametric range.*

7.3.5 *System Dynamics*

Stability of entry vehicles is paramount for successful deceleration within an atmosphere. Deceleration is first accomplished by a heatshield, with parachutes deployed to remove additional entry energy. Researchers at LaRC [33] have been developing concepts for a Multi-Mission Earth Entry Vehicle (MMEEV) to return payloads to Earth. Novel vehicle designs that perform EDL without parachutes or retro-rockets and reaction control systems are sought to reduce system complexity and increase system reliability. Typically the vehicle center of gravity (CG) is ahead of the center of pressure in the velocity vector. But as the CG moves aft as a result of vehicle design or payload placement, stability decreases. Testing was performed in the LaRC vertical wind tunnel to define limits on the location of the CG for a variety of MMEEV designs, which can be used to evaluate 6-degree-of-freedom dynamic simulations.

7.3.6 *Materials*

Testing and modeling is performed not only on materials used in spacecraft, but also on the surfaces of planetary bodies such as Mars. Advances in materials enable missions to endure increasingly extreme environments and further our understanding of material properties in those environments. Material property simulation is critical for extrapolating data from small test samples as well as for determining full-up component- and assembly-level properties. A

consortium of European researchers [34] have been developing aeroshell TPSs to deliver payloads under extremely demanding entry conditions. Hybrid TPS materials integrate an ablative layer with a ceramic matrix composite core. Plasma flow tests were performed to provide a data set for comparison to a finite element model of the test conditions.

Understanding the mechanical properties of materials in relevant environments is critical to operating on the surface of other planets. Mobility challenges with the Mars rovers have highlighted our limited knowledge of how surface materials behave in different gravity environments. D. Arthur et al. [35] have studied the mechanical properties of geo-materials in low-gravity conditions. Experiments are planned during parabolic aircraft flights to generate sub-Earth-g gravity environments to measure shear and compressive stress, and internal friction in regolith-like materials. These measurements will improve predictive indicators for surface–vehicle interactions on other planets. Figure 7-9 shows the experimental apparatus and measurement system used for conducting low-gravity materials property testing.

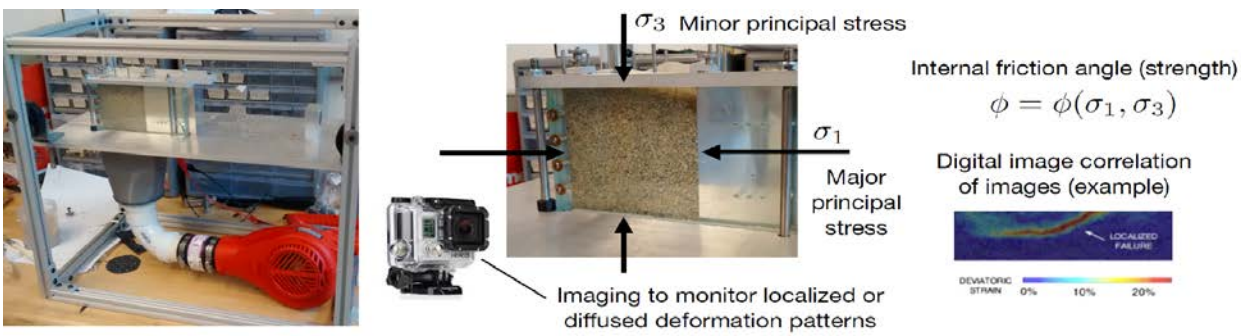

Figure 7-9. *The fluidized geo-material test facility (left) and the test article close up (right).*

7.4 Opportunities and Future Development

The development of new technologies drives much of the development of new MS&T methods. For example, inflatable aerodynamic decelerators are driving material/flow-model coupling and pushing the envelope in flight testing. New destinations require new atmospheric and chemistry models in simulations and new gas mixtures in testing.

7.5 Findings

The three methods of modeling, simulation, and testing all offer alternatives for validating the applicability of technology prior to incorporation into a flight project. Findings from the session are as follows:

1. Analytical and experimental methods complement each other in validating technology for flight missions. The common practice is to run simulations, build models, and then conduct multiple tests under varying conditions to validate the models. Experimental methods may reveal phenomena not included in the models. On the other hand, the analytical methods, once validated, can be used cost-effectively to determine performance under a broad range of conditions. These conditions may not even be realizable experimentally in the

laboratory or by Earth entry tests, but validation of a model under conditions that *can* be achieved experimentally is vital to building confidence in model prediction.

2. Securing stable funding for investment in the further development of numerical methods is challenging. Justification appears to be easier for experimental facilities. A lack of long-term strategies for simulation development occurs on both sides of the Atlantic. In the current environment, specific projects are the only source of funding for the development of most numerical tools and facilities, with the consequence that they are looking to meet only their own needs. Projects and programs are driven by requirements, resulting in a low priority for development of standard tools.
3. In situ flight measurements can spur the development of models. Flight experiments with thermocouples embedded in a heatshield can stimulate the development of models of entry-system performance and ultimately be applied to refine TPS margin and reduce mass. An up-looking camera monitoring parachute deployment can help stimulate improvements in parachute models. It is critical that the spacecraft of the future carry sensors that can aid in modelling and simulation.
4. Projects will fund development of specific features that apply to their projects. Institutions should step in and fund general development tools leveraging the project developments. Without this philosophy, we will fall behind in technology development. Currently, a long-term strategy appears to be missing. Passion and advocacy must be leveraged to secure funding.

8 Cross-Cutting Technologies

By M. Munk[22], K. Edquist[1], and B. Van Hove[23]

Challenges and progress in the development of a range of EDL technologies were presented, ranging from TPS materials and ground-testing methodologies to sample-return technology to entirely novel approaches to atmospheric entry. Packaging, ground-to-flight extrapolation, and international collaboration were emphasized in the follow-up discussion at the IPPW-11 Cross-Cutting Technologies session.

8.1 Introduction

Cross-cutting technologies (CCTs) are technologies that apply to a range of atmospheric missions such as those requiring aerocapture, aerobraking, and entry, including missions using Earth sample-return probes and landers. Specific technologies of interest include TPSs, EDL engineering instrumentation, multifunctional and high-temperature structures, extreme-environments technologies, and ground- and flight-tests and/or capabilities. Key challenges for maturing and developing EDL technologies include reducing the cost of flight testing; minimizing the growth of uncertainties when extrapolating ground-testing results to full-scale flight conditions; maximizing the return of engineering knowledge from atmospheric entry missions; and developing enabling technologies for sample-return missions and low-mass, easy-to-package flight instrumentation.

Sample-return-capsule technology development, including major challenges and progress, was presented by Airbus and other EU organizations. The emphasis was on TPS materials testing. To meet the requirements for high-speed sample return for atmospheric entry missions at the outer planets and Venus, one talk discussed Heatshield for Extreme Entry Environment Technology: HEEET is a 3-D woven carbon-fiber TPS that leverages methods developed in the textile manufacturing industry.

Three talks proposed to revolutionize entry through miniaturization: (1) direct-printed electrical circuits aiming to radically reduce mass and integration costs; (2) functional 2-D planetary landers using flat solar panels; and (3) miniaturized systems and instruments. The von Karman

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Institute (VKI) is equipping a CubeSat with an instrumented TPS to compare in-flight results with ground plasma tests and thus shed light on aerothermodynamic ground-to-flight extrapolation. NASA LaRC presented a rapid-turnaround design tool for pressure vessels required by extreme-environment missions. Another presentation on autonomous aerobraking discussed reduction of mission costs through the use of multiple low-weight, low-power accelerometers to provide environmental feedback for real-time decision-making.

8.2 Thermal-Protection System Materials

Missions to the Outer Planets in the coming decades require the development of next-generation TPS materials capable of withstanding two orders of magnitude higher heating and pressure during entry relative to the MSL entry conditions. Historically, carbon phenolic (CP) has been the only material to meet this requirement, but CP is deemed too heavy for human missions and will not continue to be available unless NASA spends significant resources to maintain the technology [36]. Other limitations of state-of-the-art ablative TPS technology include labor-intensive manufacturing and complex integration, where the TPS is commonly composed of a large number of tiles connected by gap filler [37]. Many of today's concepts for human missions to Mars (Figure 8-1) involve inflatable heatshields (currently in flight-testing on Earth [6]) and aerocapture, requiring flexible TPS materials capable of withstanding multiple heat pulses. Potential sample-return from locations beyond our Moon would involve high-speed reentry into Earth's atmosphere.

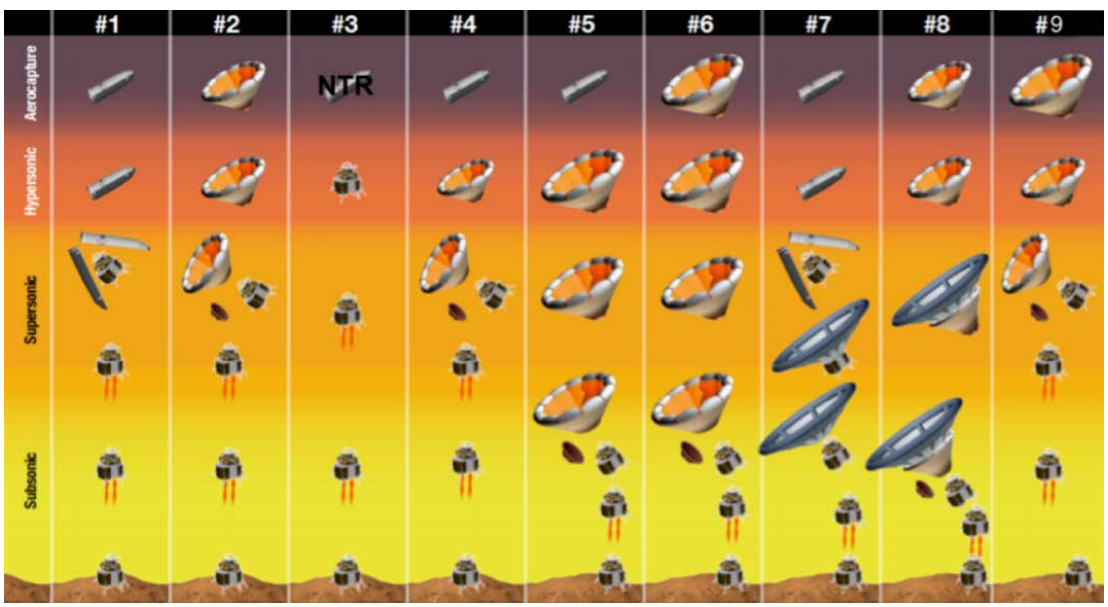

Figure 8-1. *High-mass Mars EDL concepts [37].*

New TPS materials should match the performance of CP at a reduced mass to accommodate human passengers and/or more scientific payloads, robust enough to ensure safe human flight, and easily installed on complex, possibly flexible vehicle geometries [37].

NASA is committed to deliver a 3-D woven carbon-fiber TPS (HEEET) to TRL 6 by 2017, for missions proposing to Discovery 2014. HEEET combines 3-D weaving methods developed in the

textile industry, allowing for precise, optimized fiber placement, and resin infusion if needed [38]. HEEET density can be tailored to fill the gaps between existing TPS materials. In a study for Venus missions covering a broad spectrum of entry angles, for Saturn mission concepts, and for notional high-speed sample return to Earth, ablative HEEET performed equivalently to CP at a mass efficiency of 30–50% without exhibiting any failure modes [36]. Remaining key challenges are seaming and scale-up.

A broader challenge for the development of TPS materials is the extrapolation from ground-test facilities to actual flight conditions, as illustrated in Figure 8-2. The critical issues are limited test-article scale and characterization of the flow conditions in the facility. TPS development would benefit greatly from advanced diagnostics to understand the ground-facility conditions, and to serve as inputs for numerical modeling, especially those models that extrapolate to flight conditions.

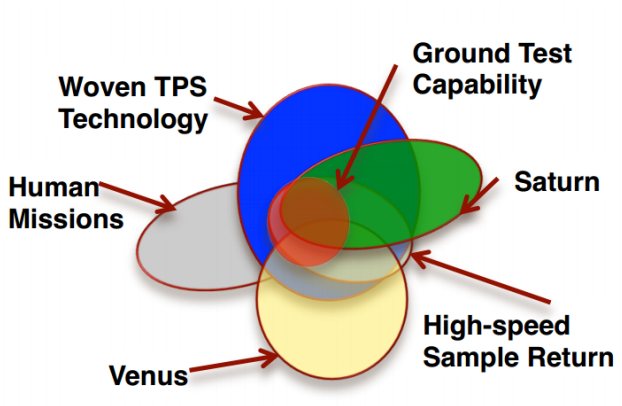

Figure 8-2. *Ground-test capability vs. flight conditions [38].*

The same challenges were considered by Airbus and other EU organizations that have been working for several years [39] on maturing sample-return-capsule technology. They considered different targets such as Mars and its moons, asteroids, and the Earth's Moon.

8.3 Flight Instrumentation and Packaging

Given the limitations of ground-test facilities, testing in the actual flight environment is a necessary step to mature EDL technologies. Current developments in flight instrumentation and lander design promise to investigate both vehicle behavior and flight conditions in more encompassing and cost-effective ways than previously possible. The developments presented at IPPW-11 included direct-write sensors, instrumented CubeSats, instrumented 2-D landers, and low-cost, low-mass accelerometers for spacecraft-state estimation during aerobraking. All of these technologies improve packaging and reduce mass, and would allow comparison of actual atmospheric and aerothermodynamic environments with ground predictions.

MesoScribe Technologies specializes in direct-write thermal spray (DWTS) technology that additively deposits materials in fine patterns to produce sensors and antennas. A wide range of materials can be deposited such as copper conductors, ceramic dielectrics and capacitors, precious metals, and semiconductors. DWTS prints conformably on 3-D substrate geometries

(Figure 8-3) of polymers, composites, and metals. Applications include high-temperature conditions, erosion-resistant and strain-tolerant embedded circuitry, diagnostic sensors (temperature, heat flux, recession, mechanical strain), heaters, and UHF/VHF/L-band antennas. They are involved in an ongoing NASA Phase II Small Business Innovation Research (SBIR) effort to develop recession-tolerant sensors for ablative TPS and a JPL/Caltech project to instrument a 2020 Mars Rover coring bit with direct-write thermocouples to measure and understand thermal conditions likely to be experienced by rock core samples.

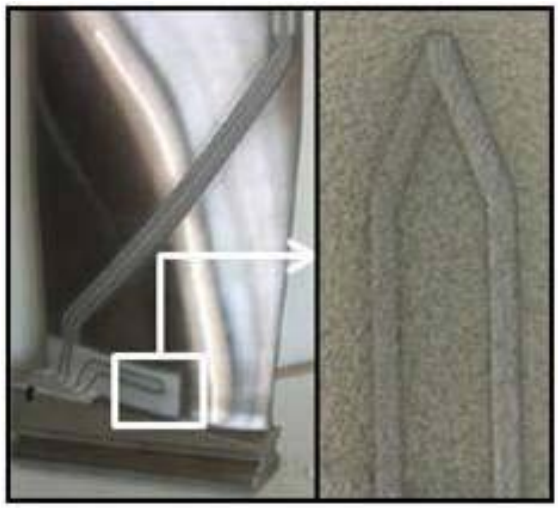

Figure 8-3. *Thermocouple deposited on a turbo machinery blade.*

Integration into existing systems can be simplified by depositing sensors compatible with existing data-acquisition systems. Because DWTS is nonintrusive, risks incurred by such measures as drilling holes through the heatshield can be avoided. Clearly, this technology has the potential to dramatically reduce mass and integration costs.

CubeSats are miniature spacecraft composed of a single unit (10×10×10 cm = 1U) or several units, and often assembled from off-the-shelf components. This strategy has driven cost down to levels that are manageable for universities and small research institutes. VKI has instrumented the 3U QubeSat for Aerothermodynamic Research and Measurements on Ablation (QARMAN) (Figure 8-4) with thermocouples, pressure sensors, a spectrometer, and a photodiode to probe rarefied and aerothermal flight environments [40]. QARMAN is a highly cost-efficient method to validate numerical codes and ground plasma tests commonly employed for larger-scale missions. QARMAN's heatshield can actually be tested in the VKI plasmatron at close to full scale.

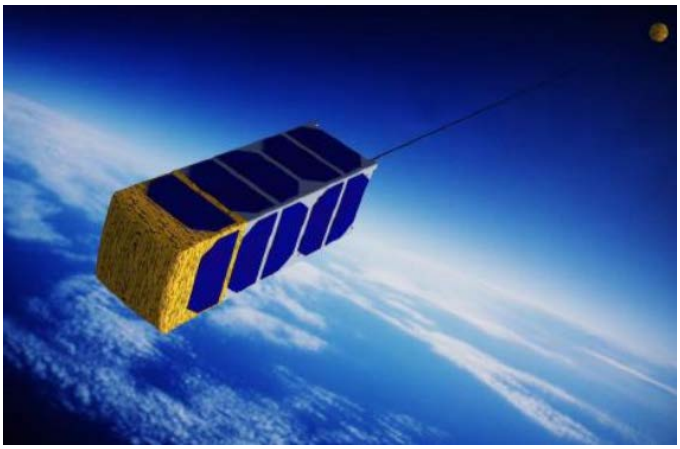

Figure 8-4. *Early concept of VKI QARMAN CubeSat [40].*

Two-dimensional surface landers are a new approach to atmospheric entry probes, measuring ~1×1 m in surface area and under 1 cm in thickness [41]. Very thin and often flexible electronic components are now commercially available, including solar cells, batteries, antennas, image sensors, gas sensors and spectrometers. Miniaturized actuators might turn sheets into spheres for wind-driven mobility. Destinations under consideration range from Mars, to asteroids, to Outer Planet moons. The prototype in Figure 8-5 successfully transmitted images, sound, altitude, pressure, and temperature data. The 2-D form factor allows stacking of dozens of landers on a single spacecraft. Previously unacceptable risk for a single lander on difficult terrain could be spread over several 2-D landers released simultaneously, with the same approach applied to enable low-cost network missions. With this technology, the main challenge is thermal management.

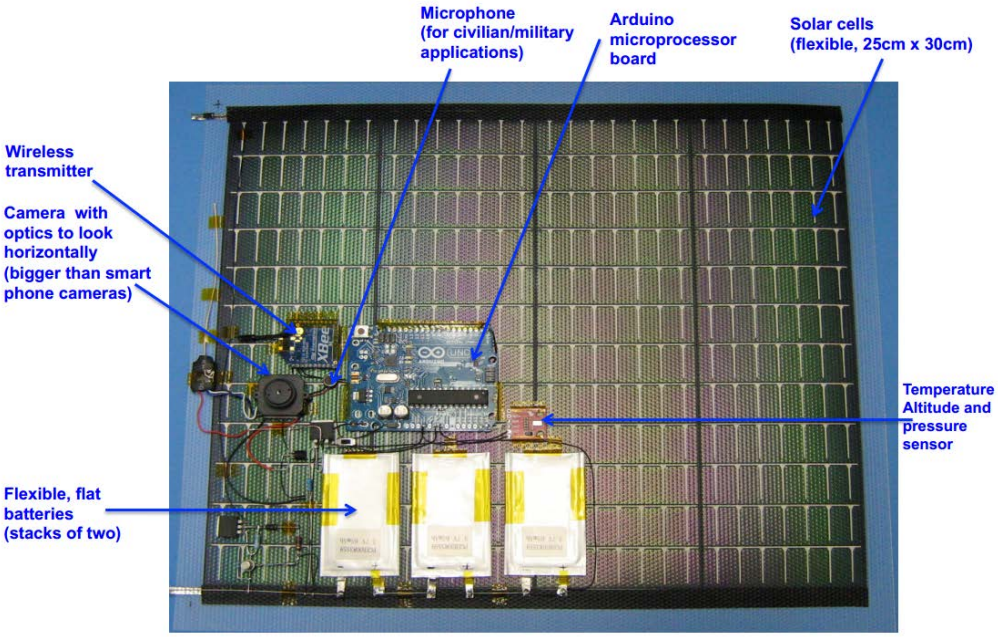

Figure 8-5. *Functional prototype of 2-D lander [41].*

A final proposed flight instrumentation concept used large numbers of low-cost, low-mass accelerometers similar to the ones used in consumer electronics. Again the idea here is to capitalize on the miniaturization and learning curves established in industry, and to perform equivalent or improved state-estimation of low-orbit satellites and aerobraking spacecraft [42] without relying on heavy, expensive inertial measurement units. Multiple accelerometers can also determine the vehicle's center-of-mass, currently not measured in EDL reconstruction [43].

8.4 Findings

The wide-ranging, cross-cutting technologies covered a multitude of topics, which generated several important findings, as summarized below:

1. Although "test as you fly" is an oft-quoted goal, it is not achievable in validating TPS performance during extreme entry scenarios at the Outer Planets. Carefully-developed numerical methods, validated by ground testing over a range of extreme conditions that simulate various aspects of the entry conditions, must be used to validate TPS performance. Simulating heat pulses with a rotating cylinder in an arc jet environment can provide additional confidence in TPS performance.
2. The commercial sector has been making great strides in sensor miniaturization. The smaller-sized sensors have challenges since the smaller size aggravates the thermal issues at the hot and cold performance extremes. On the other hand, their small size allows flying multiple sensors without significant weight penalties. Mission planners should be creative in their approach to validating these new technologies by incorporating them into larger missions. Although typical NASA missions, including those with planetary entry probes, are not drivers of this trend, given the low purchase volume of the technology, missions should be aware of technology developments that have applications to them.
3. Areas ripe for international collaboration on EDL are miniaturization, CubeSats, and autonomous aerobraking. Although International Traffic in Arms Regulations (ITAR) restrictions put some limits on collaboration, areas of little to no restriction include fundamental physics, facility characterization, and shock-wave radiation modelling. Prime examples of past international collaborations are the Hayabusa and Cassini-Huygens missions.

9 Acknowledgements

Without the hard work of the IPPW committees, our annual workshops would not succeed. Bernie Bienstock has led the International Organizing Committee for the past six IPPWs. For IPPW-11, he was ably assisted by Anita Sengupta, the US Co-Chair, and Ozgur Karatekin, the European Co-Chair. Anita also chaired the IPPW-11 Local Organizing Committee (LOC).

The Program Organizing Committee (POC) Co-Chairs, Hannes Griebel (Europe) and Aaron Morris (US) organized the workshop sessions and tasked all session co-chairs to document the results. Pat Beauchamp conceived of this report and worked with them to plan the workshop so that it could be generated. In addition, Hannes, Aaron, Pat, Bernie, and Jim Cutts edited this IPPW-11 Technology Report for consistency and accuracy.

The Student Organizing Committee was chaired in the US by Stephen Ruffin and in Europe by Jean-Pierre Lebreton. Committee co-chairs included David Atkinson in the US and Athena Coustenis in Europe.

The IPPW-11 Short Course was chaired by Ralph Lorenz. Michael Wright, along with European Co-Chair Andrew Ball and Emeritus Member Ethiraj Venkatapathy, led the Al Seiff Committee.

A final word about the core planners and organizers of the IPPWs over the years, for it is through their annual voluntary efforts that our workshops, as well as this Technology Progress Report, have come to fruition. These volunteers include David Atkinson, Jean-Pierre Lebreton, Ethiraj Venkatapathy, Jim Arnold, Bernie Bienstock, Michelle Munk, Tibor Balint, Athena Coustenis, Ralph Lorenz, Stephen Ruffin, Michael Wright, Jim Cutts, Patricia Beauchamp, Hannes Griebel, and Aaron Morris.

This report, all past IPPW presentations, and supporting materials can be found at http://solarsystem.nasa.gov/missions/ippw. Our thanks go to Phil Davis of Jet Propulsion, California Institute of Technology for organizing the site and maintaining it current.

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11 Appendix 1: Presentations and Posters by Session

All IPPW-11 presentations and posters are listed by session in Table 11-1. Sessions are listed in the order treated in sections 2 through 8 of this report. Presentations and posters within each session are listed alphabetically by last name of lead author or presenter.

Table 11-1. *IPPW-11 presentations and posters.*

§2. Missions Session Presentations and Posters	
Lead Author/Presenter	Presentation Title
P. Agrawal	*Atmospheric Entry Studies for Uranus*
S.M. Collins	*Spiral Thrusting for Momentum Control of Planetary Solar Electric Missions*
R.V. Frampton	*Design of Lander Pods for Addressing Small Bodies Strategic Knowledge Gaps*
K.A. Kipp	*Future Landing Capabilities of the Mars 2020 Entry, Descent, and Landing System*
G. Lee	*LEAF: Exploring Venus' Atmosphere with a Semi-Buoyant Air Vehicle*
R.D. Lorenz	*Twilight on Kraken*
A. Ratcliffe	*Europa Penetrator Design and Full Scale Survivability Testing*
A. Ratcliffe	*Phootprint: A European Phobos Sample Return Mission*
S.J. Saikia	*MUSEings on Uranus: An Enhanced New Frontiers Class Mission to Uranus*
H. Saranathan	*Trajectory Optimization with Adaptive Deployable Entry and Placement Technology Architecture*
T. Voirin	*INSPIRE: A Mars Network Science Mission*
Lead Author	Poster Title
M.J. Amato	*Planetary Atmosphere Probe Descent Modules for Gas and Ice Giant Missions*
D.H. Atkinson	*In Situ Probe Science at Saturn*
A.C. Barton	*Progress and Status of Google Lunar XPRIZE Mission Preparations*
G.B. Baskaran	*Potential Orbital Capture Missions to Trans-Neptunian Objects*
C.M. Bergsrud	*A Lunar Mission to Create a Constellation of Space Solar Power Satellites as a Precursor to Industrial Establishment, Resource Extraction, and Colonization*
C.M. Bergsrud	*A Mission to Create a Constellation of Space Solar Power Satellites as an Enabler for Martian Exploration Activities*
D.J. Blette	*Mars Active Hydrology Exploration Mission*
S.C. Creech	*SLS and Planetary Exploration*
K. Gonyea	*SPLAT: The Sample Probe for Landing and Testing*
C. Holstein-Rathlou	*Atmospheric Properties Reconstruction from the Mars Science Laboratory Entry, Descent and Landing*
L. Li	*SPAS: Saturn Probe for Atmospheric Science*
C. Miller	*Planned Lunar Impacts: Scientific Value and Ground-Based Observation Limits*
O. Mousis	*Scientific Rationale and Concepts for an in Situ Saturn Probe*

Lead Author	Poster Title
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A. Rajguru	*Operations cost Reduction for a Jovian Science Mission Using CubeSats*
S.J. Saikia	*Marching Towards Troy: Exploration of Jupiter Trojan Asteroids*
D. Sokol	*Venus Atmospheric Maneuverable Platform (VAMP)—Air Vehicle Concept and Entry ConOps*
A. Solomonidou	*Mid-Latitude Regions on Titan as Promising Landing Sites for Future in Situ Missions*
J. Straub	*Deep Space Orbital Service Model for Virtual Planetary Science Missions*
E. Yakut	*Meteorological Observations and Establishing a Base for Future Mars Missions*
§3. Science and Engineering Instrumentation Session Presentations and Posters	
Lead Author/Presenter	Presentation Title
S.W. Asmar	*The Martian Interior Structure from Landed Probe Doppler Tracking*
G.B. Bailet	*Re-Entry Platform for Radiation Studies*
A. Guelhan	*Combined Sensor Package COMARS+ for Measuring Aerothermal and Radiation Loads on the ExoMars EDM Capsule Back Cover*
P.R. Mahaffy	*In Situ Techniques for Measurements of Noble Gas and Nitrogen Isotopes in Planetary Environments: Recent Advances*
E. Trifoni	*Concept of an Innovative Photoluminescent Sensor for Radiative Heat Flux Measurement During Super-Orbital Re-Entry*
K. Zacny	*Sample Acquisition and Caching Architectures for the Mars 2020 Mission*
Lead Author	Poster Title
D.H Atkinson	*Future Planetary Probe Doppler Wind Experiment Techniques Utilizing Advanced Tracking and Ranging Subsystems*
J. Castillo-Rogez	*Decadal and SKG Science with Next Generation Low Cost Small Platforms*
P.O. Omaly	*ICOTOM: Narrow Band Infrared Radiometer*
S. Rafkin	*The Atmospheric Characterization for Exploration and Science (ACES) Instrument Suite for Mars*
S. Wayne	*Balloon Measurements of Winds in Planetary Atmospheres*
K. Zacny	*Comet Surface Sampling Technologies*
§4. EDL Technologies Session Presentations and Posters	
Lead Author/Presenter	Presentation Title
D. Bose	*Mars Entry, Descent, and Landing Instrumentation (MEDLI): Return on Investment*
A. Chen	*Mars 2020 Entry, Descent, and Landing Overview*
W.S. Gullotta	*Resettable Landing Gear for Mars Hopper*
S.J. Hughes	*Terrestrial HIAD Orbital Reentry (THOR) Flight Test Opportunity*
C.D. Kazemba	*A Versatile 3D-Woven Carbon Fabric for Broad Mission Application of ADEPT*
J.S. Lingard	*Supersonic Parachute Aerodynamic Testing and Fluid Structure Interaction Simulation*
M.M. Munk	*EDL Technology Investments within NASA's Space Technology Mission Directorate (STMD)*
A. Raiguru	*Entry, Descent and Landing of an Amphibious Quadcopter Swarm for the Exploration of Titan*
S. Woicke	*A Stereo Vision Based Hazard Detection Algorithm for Future Planetary Landers*
T.Y. Yamada	*Hayabusa-2 Reentry Capsule and Its Verification Tests*
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H.K. Ali	*In Situ Magnetohydrodynamic Energy Generation for Planetary Entry Vehicles*
R.A.S. Beck	*Update on Conformal Ablative Thermal Protection System for Planetary and Human Exploration Missions*
T.B. Boghozian	*Alternative High Performance Polymers for Ablative Thermal Protection Systems*
A. Bombelli	*Entry Trajectory Planner for High Elevation Mars Landing*
R. Buchwald	*A Landing Platform with Robotic Self-Leveling Capability*
T. Fisher	*Preliminary EDL Aeroshell Design Performance from a Newtonian Theory Simulation Tool*

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J.C. Foster	*Where's Your EDL Data?*
J. Heilimo	*RITD—Adapting Mars Entry, Descent and Landing System for Earth*
S. Luque Ribas	*Guided Descent to Mars. Vision-Based Navigation System for a Mars Probe*
K.J. Morse	*Validation of a Model for the Impact Landing of a Tensegrity Landing System*
M.K. Murphy	*Depressed Aeroshell Forebody Geometries for the Generation of Lift*
C. Park	*Conjecture on the Appearance of the Galileo Probe's Entry and Descent in to the Jovian Atmosphere*
E.D. Rodriguez	*AVCOAT Density Characterization for Orion Multi-Purpose Crew Vehicle*
S.J. Saikia	*Enabling Venus In Situ Missions Using Mechanically Deployed Aerodynamic Decelerator*
S.A. Sepka	*Development of FIAT-Based Parametric Thermal Protection System Mass Estimating Relationships for NASA's Multi-Mission Earth Entry Concept*
Y.M. Yignot	*ExoMars Heatshield: From Design to Manufacturing*
§5. Inflatables and Deployables Session Presentations and Posters	
Lead Author/Presenter	Presentation Title
J.O. Arnold	*Arcjet Testing of Woven Carbon Fabric Joints for Use on Adaptive Deployable Entry Placement Technology (ADEPT)*
R. Diaz-Silva	*Standalone Simulations of SIAD Aeroelastic Response Using LS-DYNA*
R.A. Dillman	*Planned Flight of the Terrestrial HIAD Orbital Reentry (THOR)*
B. Smith	*ADEPT for Secondary Payloads*
G.T. Swanson	*Overview of the 6-Meter HIAD Inflatable Structure and Flexible TPS Static Load Test Series*
B.C. Yount	*Deployment Testing of the ADEPT Ground Test Article*
Lead Author	Poster Title
L.B. Bolisay	*Venus Atmospheric Maneuverable Platform (VAMP)—Stowage/Deployment Concepts and Materials Investigation*
§6. Sustained Flight Session Presentations and Posters	
Lead Author/Presenter	Presentation Title
J. Balaram	*Rotorcrafts For Mars Exploration*
L. Matthies	*Titan Aerial Daughtercraft (TAD) for Surface Studies from a Lander or Balloon*
D. Mimoun	*Venus Geophysical Explorer: A Venus Interior Structure Mission Using Balloons*
M.T. Pauken	*Development and Testing of a Titan Super Pressure Balloon Prototype*
P.T. Tokumaru	*Fixed and Rotary Wing Flight of Small Air Vehicles on Mars, Venus, and Titan*
P.B. Voss	*Altitude-Controlled Balloons for Long-Duration Flights on Venus*
Lead Author	Poster Title
L. Mathies	*Venus Guided Aerosonde (VGA) for Landing Site Reconnaissance*
§7. Modeling, Simulation, and Testing Session Presentations and Posters	
Lead Author/Presenter	Presentation Title
L.W. Kohlman	*High Rate, Low Temperature Testing and Modeling of Water Ice for High Speed Ballistic Probes*
R. Buchwald	*Simulation-Based Landing System Verification: About the Challenges on Non-Linear Error Estimation*
A. Jaramillo-Botero	*Hypervelocity Impact Effects on Space Mission Instrumentation*
A. Sengupta	*Plume Impingement Induced Surface Erosion during Retro-Propulsive Landings on Mars*
S. Tardivel	*Modeling of Asteroid Surfaces to Understand Landing Operations*
L. Witte	*A Stochastic Model for the Landing Dispersion of Hazard Detection and Avoidance Capable Flight Systems*
L. Glabb	*Multi-Mission Earth Entry Vehicle Subsonic Dynamic Stability Testing and Analyses*
B. Van Hove	*Mars EDL Reconstruction from Flight Data: Uncertainty Quantification*

Lead Author	Poster Title
M.T. Pauken	*Expendable Cooling for a One-Day Venus Lander*
S.V. Perino	*A Structural Concept Study for Future Planetary Probes and Sample Return Vehicles*
G.A. Allen	*Uranus Atmospheric Model for Engineering Application*
G. Pinaud	*HYDRA: Macroscopic 3D Approach of Light Weight Ablator*
F.M. Ramirez	*Position Analysis of a Pico-Satellite for Optimum Solar Illumination*
D. Arthur	*Fundamental Characterisation of Planetary Surface Material in Microgravity Environments*
M.J. Gasch	*Thermal Testing of Planetary Probe Thermal Protection System Materials in Extreme Entry Environments*
	§8. Cross-Cutting Technologies Session Presentations and Posters
Lead Author/Presenter	Presentation Title
J-M Bouilly	*Sample Return Capsules Challenges and Technologies*
E. Venkatapathy	*Heat Shield for Extreme Entry Environment Technology (HEEET) for Near-Term Robotic Science Missions and Longer-Term Human Missions*
J.A. Brogan	*MesoScribe: Direct Write Sensors for Space and Probe Applications*
A. Sengupta	*Two-Dimensional Planetary Surface Landers*
J Samareh	*Pressure Vessel Design Concepts for Planetary Probe Missions*
I. Sakraker	*Atmospheric Entry Aerothermodynamics Flight Test on CubeSat Platform*
B. Pigneur	*Multiple Sensors for Absolute Measurement of Aerobraking Spacecraft State Estimation*
Lead Author	Poster Title
J.J. Nyago	*Enhancement of Knowledge and Skills of University Educators, Research and Application Scientists in Both the Physical and Natural Sciences as Well as in Analytical Disciplines*
D. Kuznetsova	*A Model for Meteoroid Atmospheric Entry and its Application to Simulate the Capabilities of an Orbiter for Meteors Monitoring*
C.M. Sunday	*Surface-Lander Interactions on Small Bodies*
G. Gonzales	*Thermal Testing of Woven TPS Materials in Extreme Entry Environments*
J. Straub	*Autonomous Control for Space Solar Power for a Planetary Science Mission*
J. Straub	*Towards Autonomy for Planetary Science: Scientist Characteristics and Autonomy Acceptance*

12 Appendix 2: Acronyms and Abbreviations

1U	one-unit CubeSat: a cube 10 cm in length, width, and height
2-D, 3-D	two-dimensional, three-dimensional
ACES	Atmospheric Characterization for Exploration and Science
ADEPT	Adaptive, Deployable Entry and Placement Technology
AGC	ambient-gas compression
AO	Announcement of Opportunity
ARC	Ames Research Center
AVCOAT	ablative heatshield material created by Avco (now by Textron)
CCT	cross-cutting technology
CFD	computational fluid dynamics
CNRS	Centre National de la Recherche Scientifique (National Center for Scientific Research)
COMARS+	combined sensor assembly payload for Mars atmospheric entry
ConOps	concept of operations
CP	carbon phenolic
DKP	Duffin-Kemmer-Petiau oscillator
DWTS	direct-write thermal spray
EADS	European Aeronautic Defence and Space Company
EDL	entry, descent, and landing
EDM	EDL Demonstrator Module
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre

EU	European Union
EVE	European Venus Explorer
ExoMars	ESA-led 2016 Mars mission
FIAT	Fully Implicit Ablation and Thermal Analysis
GPMS	Galileo Probe Mass Spectrometer
GTA	ground-test article
HDA	hazard detection and avoidance
HEART	High-Energy Atmospheric Reentry Test
HEEET	Heatshield for Extreme Entry Environment Technology
HIAD	hypersonic inflatable aerodynamic decelerator
HTA	heavier than atmosphere
HYDRA	Hybrid Ablative Development for Re-Entry in Planetary Atmospheric Thermal Protection
ICOTOM	Infrared CO_2 Measurement
IHF	Interactive Heating Facility
INSPIRE	Interplanetary NanoSpacecraft Pathfinder in Relevant Environment
IPPW	International Planetary Probe Workshop
IRVE	Inflatable Reentry Vehicle Experiment
ISAE	Institut Supérieur de l'Aéronautique et de l'Espace (Institute of Aeronautical and Space Engineering)
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory, California Institute of Technology
JUICE	Jupiter Icy Moons Explorer
L/D	lift-to-drag ratio
LaRC	Langley Research Center
LCD	liquid crystal display
LDSD	Low-Density Supersonic Decelerator

LEAF	Lifting Entry/Atmospheric Flight
LGC	lift-gas compression
LOC	Local Organizing Committee
LPC2E	Laboratoire de Physique et Chimie de l'Environnement et de l'Espace (Laboratory of Physics and Chemistry of the Environment and Space)
LS-DYNA	advanced general-purpose multiphysics simulation software package developed by LSTC
LSTC	Livermore Software Technology Corporation
LTA	lighter than atmosphere
M4	ESA M-Class (medium-sized) mission
MEDLI	Mars Entry, Descent, and Landing Instrumentation
MMEEV	Multi-Mission Earth Entry Vehicle
MOLA	Mars Orbiter Laser Altimeter
MREP-2	Mars Robotic Exploration Preparation Programme 2
MS&T	modeling, simulation, and testing
MSL	Mars Science Laboratory
MUSE	Mission for Uranus Science and Exploration
NASA	National Aeronautics and Space Administration
NF	New Frontiers
NGS	noble gas cell
NIAC	NASA Innovative Advanced Concepts
PICA	phenolic impregnated carbon ablator
POC	Program Organizing Committee
QARMAN	QubeSat for Aerothermodynamic Research and Measurements on Ablation
QMS	quadrupole mass spectrometer
RITD	Re-entry: Inflatable Technology Development
ROB	Royal Observatory of Belgium
RPS	radioisotope power system
SAM	Sample Analysis at Mars
SBIR	Small Business Innovation Research

SIAD	supersonic inflatable aerodynamic decelerator
SKG	Strategic Knowledge Gap
SLS	Space Launch System
SMS	sample manipulation system
SP	super-pressure (balloon)
SPAS	Saturn Probe for Atmospheric Science
SPLAT	Sample Probe for Landing and Testing
SSDS	Supersonic Disk Sail
SSIT	solid sample inlet tube
STMD	Space Technology Mission Directorate
TAD	Titan Aerial Daughtercraft
TEAMS 2	Technology, Engineering and Aerospace Mission Support 2
THOR	Terrestrial HIAD Orbital Reentry
TiME	Titan Mare Explorer
TLS	tunable laser spectrometer
TPS	thermal-protection system
TRL	technology readiness level
TSSM	Titan Saturn System Mission
UHF	ultrahigh frequency
UK	United Kingdom
US	United States
USA	United States of America
VALOR	Venus Aerostatic-Lift Observatories for in Situ Research
VAMP	Venus Atmospheric Maneuverable Platform
VGA	Venus Guided Aerosonde
VHF	very high frequency
VKI	von Karman Institute
ZP	zero-pressure (balloon)

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