Technologies for Outer Planet Missions: A Companion to the Outer Planet Assessment Group (OPAG) Strategic Exploration White Paper

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1.0 EXECUTIVE SUMMARY

The richness and diversity of the outer planets and their satellites are second to none in the Solar System, but to explore the outer solar system requires advanced technology. The Outer Planet Assessment Group (OPAG) recommends the following to enable this exploration:

1. NASA should work with the relevant agencies to ensure that Pu-238 production is restarted and provides enough material for future outer planet missions. In particular, NASA should flight-qualify ASRG power systems.
2. A focused technology program for the next Outer Planet (OP) Flagship mission after the Europa Jupiter System Mission (EJSM) should be initiated in order to be ready for a launch in the mid-2020s. Current planning indicates a mission to Titan and Enceladus will be the highest priority. NASA should fund development of the montgolfière balloon, the autonomy required to operate it at Titan, landing technologies required for sampling the high latitude lakes, dunes and cryovolcanic regions and components operable in extreme environments. NASA should also initiate a program in cryogenic sample acquisition and sample handling.
3. NASA should expand the funding of communication and radio science technologies required for the outer planets, especially making Ka band operational and furthering proximity and direct-to-Earth communication technologies.
4. NASA should continue to invest in development of underlying technologies (thrusters, power and control, propulsion technologies) for solar electric propulsion, to bring these systems to flight readiness and to make the capability affordable to and within the risk postures of different mission classes.
5. NASA should invest in aerocapture technologies and conduct a space-flight validation of aerocapture in advance of the decision points of identified missions.
6. For planetary probes, OPAG recommends investment in the development of alternative thermal protection systems (TPS) materials, and periodic limited manufacturing and testing demonstrations to ensure heritage TPS manufacturing is kept current.
7. NASA should achieve a better balance between component development, *in situ* and remote sensing (active and passive) instrument definition, and instrument development, with a focus on demonstrating complete instrument *systems* and bridging the gap to flight. An OP instrument program should focus on developing and maturing low mass/power instrument systems that have high resolution and sensitivity, raising the TRL to ≥6.

2.0 OVERVIEW

The challenges common to all OP missions—large distances, long flight times, and stringent limitations on mass, power, and data rate—mean that all missions can significantly benefit from technical advances in a number of broad areas. Since technology development timescales are long, it is most productive to base technology requirements on the expected general characteristics of future missions. While the Flagship mission concepts are better understood, an estimate of the needs for competed small class (Discovery) and medium class (New Frontiers) missions can be included in constructing an effective technology investment plan.

Technology investment priorities are guided by the requirements established in mission and system studies that are focused on the highest priority science objectives. The next OP mission (after EJSM) would involve orbiting the saturnian satellites, Titan and Enceladus. The nominal mission concept involves orbiting and *in situ* elements, as confirmed by the science panel for the 2008 Titan Saturn System Mission (TSSM) concept review. *In situ* elements are envisioned to be aerial and landed platforms with sampling capabilities. New Frontiers or small flagship missions that may be realizable in the 2013-2022 timeframe include shallow atmospheric probes of the giant planets and an advanced flyby of an ice giant and its satellites. Subsequent potential OP large-class missions include orbiting Neptune and Uranus, landing on Enceladus and Europa, and probing deep into the atmospheres of the giant planets.

The breadth of technology needed for OP exploration clearly calls for an aggressive and focused technology development strategy that aligns with the Decadal Survey recommended mission profile, and includes technologies developed by NASA, as well as acquisition of applicable technologies from other government and commercial sectors. Some technologies of

Table 1. Technology Priorities for Outer Planet Exploration.

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

UP Ultimate priority—Without new Pu-238, no further exploration beyond Jupiter will occur subsequent to EJSM.
1 Highest priority—New developments are required for all or most future OP missions.
2 High priority—Either the applications are more limited or NASA could effectively leverage existing work.

importance to OP exploration are currently being developed by NASA's Science Mission Directorate (SMD), while some critical technologies have yet to be funded. Table 1 summarizes the technology priorities for OP exploration. A brief discussion of these technologies follows, but more information can be found in an extended document which will be available on the OPAG website. This work is the culmination of a multi-institutional effort spanning several months.

3.0 SPACECRAFT SYSTEMS TECHNOLOGIES

3.1 Power

Advanced power system technologies are required to enable and enhance many OP missions that require power systems with mass and volume efficiency, long-life capability and the ability to operate in extreme environments (e.g., temperatures, pressures). The power system technologies required include: radioisotope power systems, high efficiency solar arrays, high energy density storage systems, and power electronics.

3.1.1 Radioisotope Power Systems (RPS)

Most OP missions, because of the extreme environments they explore and limited solar insolation they experience, are likely to require RPSs for furnishing adequate electrical power. Missions beyond Saturn would benefit greatly from advanced >100 watt radioisotope power systems with long life capability (>20 years), high conversion efficiency (>15%) and high specific power (>8 W/kg). Some future planetary sensor network missions would require small long-life (milli- or multi-watt) RPSs. In particular, unique science opportunities using small measurement platforms at Titan, such as buoyant-gas weather balloons, and a network of small geophysical landers, analogous to those proposed for Mars and the moon, would be enabled by small RPSs of the few-10 watt class. In addition, some missions could require kW-class RPSs for ion propulsion applications. NASA-SMD is currently developing a 140 W Advanced Stirling Radioisotope Generator (ASRG) capable of providing 6–8 W/kg and 30% efficiency. NASA-SMD is also developing advanced thermoelectric (TE) and thermo-photovoltaic (TPV) conversion technologies (static power-conversion systems) that are capable of providing >6 W/kg and >10 % efficiency.

Future NASA-SMD RPS technology efforts should, foremost, validate ASRG technology for long-life flagship and other missions. Such efforts should, in addition 1) mature and validate advanced TE and TPV technologies for long-life and high reliability missions, 2) develop small (milli-/multi-watt) radioisotope power generators for sensor networks, and 3) develop kilowatt class radioisotope power generators for radioisotope electric propulsion (REP) missions. Currently, there is an insufficient supply of Pu-238 to fuel all potential RPS systems that would be base-lined for future OP missions, and none will be left for any civilian space application after the Jupiter Europa Orbiter (JEO) portion of EJSM (Hoover et al. 2009. *Radioisotope Power Systems: An Imperative for Maintaining U.S. Leadership in Space Exploration*. National Academies Press, ISBN 0-309-13858-2, http://www.nap.edu/catalog/12653.html). As of this writing, whether Pu-238 production will be restarted by DOE in the near term is uncertain, and higher efficiency systems cannot by themselves mitigate a complete lack of plutonium. Future availability of Pu-238 is a make-or-break issue for OP exploration beyond Jupiter.

3.1.2 Solar Arrays

Planetary missions beyond 3AU require solar cells that can operate efficiently at low solar intensities and low temperatures (LILT). High power solar electric propulsion (SEP) missions require advanced solar arrays with higher efficiency (>35%), and high specific power (>300 W/kg). No significant efforts are presently underway at NASA to develop advanced solar cells and arrays required for future OP exploration missions.

3.1.3 Energy Storage Systems

Advanced primary batteries with high specific energy (>500 Wh/kg) and long storage-life capability (>15 years) are required for future planetary probes and lander missions. OP surface missions require primary batteries that can operate at temperatures < –80°C. Advanced rechargeable batteries with high specific energy (>200 Wh/kg) and long-life capability (>20 years) are required for future orbital missions. No significant efforts are presently underway at NASA to develop advanced primary and rechargeable batteries required for future missions, but NASA must increase the lifetime and robustness of commercial batteries for OP applications.

3.1.4 Power Electronics Technologies

Advanced power conversion, management and distribution technologies with higher power density (>150 W/kg), higher conversion efficiency (>90%), and capability to survive in extreme environments are needed for most of the future OP missions. Future SEP missions require power systems with high power capability (> 20 kW), high voltage (> 120 V) and high power density. Again, no significant efforts are presently underway at NASA to develop these advanced power conversion, management, distribution technologies or advanced packaging concepts for high power devices for future solar system exploration missions.

Recommendation 1 (Power): **OPAG strongly recommends that NASA work with the relevant agencies to ensure that Pu-238 production provides enough material for future OP missions, and fully support the validation of the ASRG system for OP applications, including the development of small (milli-/multi-watt) radioisotope power generators for sensor networks. In addition, NASA should adapt and complement industry-developed advanced solar cell and array technology program, advanced battery technology, and advanced power conversion and distribution technologies program for OP missions.**

3.2 Transportation Technologies

3.2.1 Electric Propulsion

Electric Propulsion (EP) enables missions requiring large in-space velocity changes over time and can often provide enhanced and enabling trajectories to the outer planets. This technology opens up mass and trip-time trades, offering major performance gains and significant improvements to mission capabilities. Development efforts are underway, but sustained investments are still required. The resulting systems would provide substantial benefits to near-term SEP and long-term REP OP missions.

3.2.2 Aerocapture

Aerocapture is enabling for a Neptune orbiter and useful for other missions, since reducing the very high arrival velocity with propulsion requires more fuel than current launch vehicles can inject. It uses high-heritage elements of previous spacecraft and hypersonic entry missions, but also involves one single unproven element: the exit phase of the atmospheric pass. An Earth flight validation would retire risk for immediate use.

3.2.3 Astrodynamics

Funding for application of the principles of celestial mechanics to the problem of the motion of spacecraft has been largely limited to the development and operations phases of flagship missions. Early funding for astrodynamics studies would produce new techniques *prior* to formulation of missions, which could lead to novel and exciting concepts.

***Recommendation 2 (Transportation)*: SMD should continue its development of EP components and consider development of an off-the-shelf multi-mission SEP module (not only for the OP missions) that would be available to users with acceptable cost and risk constraints. Aerocapture development should focus on needs identified for Titan and Neptune, and risk reduction resulting in flight readiness is strongly encouraged to open up this mission enhancing, and for Neptune, enabling technology.**

3.3 Communications

Deep Space communication between Earth and the outer planets poses notable challenges for retrieving science data sets. Additionally, communications for *in situ* scenarios are particularly challenging due to resource and geometric constraints. OPAG recommends that NASA develop the technology and implement the following (in priority order):

- Baseline Ka-band communications, which can enable 4+ times higher data rates than X-band, for missions that have high data rate science return requirements.
- Invest in maturing the next generation transponder supporting: 10 Mbps uplink; 100 Mbps downlink; integrated proximity and direct-to-Earth communications (currently requires two devices); integrated radio science for atmospheric and gravity experiments with few-micron/sec two-way Doppler capabilities.
- Sustain and accelerate Deep Space Network (DSN) antenna arraying: develop Ka-band and X-band uplink and downlink arraying equivalent to a 70 meter (or larger) aperture.
- Demonstrate and mature the technology required for OP optical (laser) communications flight transceivers for very high science data return (up to two orders of magnitude greater rate) in direct-to-Earth-mode from orbiters and the planetary surface, and access-link from surface-to-orbiters, with RF telecom for lower rate spacecraft telemetry.
- Mature and advance *higher-power* transmitters.
- Develop high-gain, light-weight, deployable Ka-band antenna technologies, 5-meter or larger for long distance, direct to Earth links.
- Implement advances in data compression to more efficiently transmit science data to Earth.
- Develop UHF antenna designs and relay systems with increased efficiencies for relay and proximity communications UHF transmitters.
- Baseline more effective error-correcting coding techniques for missions.

***Recommendation 3 (Communications)*: NASA should expand the funding of communication and radio science technologies required for the OP, especially making Ka band operational and furthering proximity and direct-to-Earth communication technologies.**

3.4 Planetary Protection (PP)

Forward contamination requirements can drive the cost and complexity of OP missions. These requirements not only could impact *in situ* exploration, but they could also impact orbital spacecraft that must avoid or be designed for potential impact with targets of biological interest such as Europa, Titan, and Enceladus during their planetary system tours. Although the Mars Exploration Program (MEP) is developing new PP technologies and approaches to address requirements for future Mars missions, they are likely to be very different from planetary protection requirements for OP missions and therefore insufficient. In part, this disparity stems from the unique environments that these targets present. System-level technologies for forward PP would require early investment so that they could be incorporated into the spacecraft designs early in the study phase. For example, appropriate PP approaches for the detection, quantification, and accounting of terrestrial organisms on spacecraft need to be determined and developed. Development of integrated PP approaches for spacecraft assembly, as well as integration and test are also required to eliminate re-contamination to ensure that the spacecraft system is at the necessary level of sterility when it reaches the target object.

Recommendation 4 (Planetary Protection): **OPAG strongly recommends that PP requirements to the OPs be defined early, especially for Titan and Enceladus, and that investments be made to jointly develop solutions and technologies for PP and contamination control.**

4.0 TECHNOLOGIES FOR *IN SITU* EXPLORATION

Future missions to the outer planets require direct access to the atmosphere and surface of planets and satellites. This is achieved through the use of landers, aerial platforms, and planetary probes, which are enabled by a family of technologies for *in situ* exploration.

4.1 *In Situ* Platforms

4.1.1 Mobility

Previous studies have identified the montgolfière balloon as a key element in a comprehensive Titan exploration strategy with very high science value. The most recent 2008 joint NASA/ESA TSSM study provided a compelling concept for implementation of a montgolfière at Titan. While orbiter and lander elements appear to have significant flight heritage, a balloon has not been flown on Titan and will require focused study and risk reduction efforts. Based upon the high priority of Titan science, results from many years of mission studies, and current state of technology readiness, NASA and ESA review boards have recommended the following be pursued to enable a balloon mission at Titan within foreseeable budgets and at acceptable risk: 1) conduct focused studies of Titan balloon mission options, leveraging from previous work, to focus on selection of architecture(s) that best achieve highest priority science and 2) initiate substantial sustained investment in risk reduction efforts needed to mature the Titan balloon concept for flight readiness. Risk reduction efforts include the following: balloon deployment and inflation, thermal performance margins, packaging and thermal management inside the aeroshell, interface complexity between balloon, RPS and aeroshell and integration of the RPS into the balloon.

Additionally, long-term operation of mobile platforms would be faced with challenges because of the long latency in communications, communications blackouts due to Titan rotation and occlusion by Saturn, the absence of a magnetic field, low surface illumination conditions, and the lack of high-resolution orbital maps. Consequently, autonomous navigation and control and autonomous onboard science capabilities for data prioritization and opportunistic observations will be critical. Linking scientific observations to their coordinates on Titan would significantly enhance the science value of an *in situ* mission.

4.1.2 Landers

The geological, geophysical and presumed geochemical diversity of Titan's surface suggest at least three surface types that should be sampled by a future mission to Titan: 1) a Titan lake lander/submersible; 2) a dune lander, and 3) a lander positioned near suspected cryovolcanic structures. In all cases, objectives involve geophysical measurements as well as sampling and analytical chemistry in a cryo-environment. NASA should initiate a program in cryogenic sample acquisition and sample handling. Each of the Titan environments has its own unique requirements that need to be developed to achieve and maintain scientific integrity of samples prior to analysis.

Recommendation 5 (In Situ Platforms): **OPAG recommends a sustained investment in this decade that would result in the demonstration of technical readiness for launch of a Titan balloon, and that NASA support the development of key autonomy capabilities required for a Titan balloon. Further, OPAG recommends that NASA invest in focused stud-**

ies of Titan lander concepts and associated entry, descent landing technologies, and mature the technologies necessary for surface sampling in different environments.

4.2 Entry Systems and Planetary Probes

Because some of the OP targets have atmospheres and some are airless bodies, entry system technologies include aeroshell and propulsion elements. Entries at smaller planets and satellites (e.g., Titan) could be achieved in most cases using existing TPS technologies, since the gravity field and entry velocities are sufficiently low. Certain architectures call for impactors (e.g., to Enceladus), where high g-load tolerant components are necessary. For aeroshells, suitable TPS should mitigate high convective and radiative heating and a long heat pulse.

Key technology areas for future entry probes are development of 1) components and instrument systems that can withstand the high temperature/pressure environment during entry 2) strong, lightweight materials that can provide improved payload mass fraction and 3) thermal protection and control materials necessary to maintain the probe interior at moderate temperatures for missions lasting several hours. The highest velocity entry, at Jupiter, requires high-density carbon-phenolic (H-CP) similar to that used on the Galileo mission (made from a now-discontinued qualified rayon, whose production capability no longer exists). Probe entries to other giant planets face ~10 times lower heating rates, but still require H-CP. Finding an alternate to heritage H-CP is a long lead item and would require extensive technology maturation and ground testing. Investment in developing an alternative to heritage H-CP is required as well as developing enhanced test facilities which would demonstrate and test TPS production.

Recommendation 6 (Entry Systems and Planetary Probes): **OPAG recommends investments be made in key technologies for entry systems and planetary probes; extreme environment systems, miniaturized, low power integrated sensors, transmitters, avionics, thermal materials, power management systems, entry, descent and landing technologies, and on-board processing.**

4.3 Extreme Environment Technologies

Low temperatures affect the operation of a large fraction of all the chemical, electronic, and mechanical components and can reduce the lifetime of components and sub-systems. Warm boxes, which increase the mass, have to be added to protect the components. New technologies can enable systems to tolerate operation in very cold environments. Low–temperature *in situ* missions to Titan, Enceladus, Europa and Triton would be strongly enhanced by development of components such as actuators, motors, and instruments which can operate at low temperature. Similarly, for planetary probe missions, components and subsystems have to withstand extremely high temperatures and pressures.

Recommendation 7 (Extreme Environments): **OPAG recommends that NASA fund a technology program focusing on designing and testing low (and high) temperature components and sub-systems that could be used throughout the spacecraft (or probe) and instruments. Initiating this program as soon as practicable would have a major impact on the feasibility of a Titan Flagship mission and would also enable New Frontiers missions.**

5.0 SCIENCE INSTRUMENTS

There are serious gaps in support of instrument programs, particularly in taking development from concept stage to TRL 6. In addition, programs that have historically funded instrument component technologies, which are crucial for developing the appropriate capabilities, no longer exist.

5.1 Remote Sensing

Remote sensing experiments are essential to any OP mission. To increase science return and achieve efficient mission designs, instruments have to be low in mass and require low power. For Titan missions, the instruments are required to see through the atmosphere to the surface as well as analyze the atmosphere and measure its gravitational field. Instruments for both Titan and Enceladus have to be capable of high spatial (and in the case of spectrometers, high spectral) resolution and high sensitivity to answer the scientific questions that have emerged from Cassini. Such instruments do not currently exist at a high TRL levels.

5.2 *In Situ* Instruments

In situ instruments that facilitate atmospheric, surface and subsurface measurements have to tolerate extreme environments ranging from severe temperatures (<100–700 K), pressure (0–100 atmospheres), radiation, high-g loading for impactors (20,000–80,000 g), and possibly corrosive environments. Key technologies for such instrument systems include: cryogenic sample acquisition from atmospheres and surfaces; sample distribution/interrogation front ends; actuators; instrument electronic devices; battery technology; circuit technologies including packaging technologies for high-g impact loads such as impactors/penetrators; sample transfer staging technologies. Reducing the volume, mass and power requirements of instrument systems are essential for OP missions involving landers, mobility platforms, cryobots, or probes and penetrators in order to maximize the science return. Key geophysical instruments (e.g., seismometers and magnetometers) and analytic instruments systems (e.g., high resolution/sensitivity gas chromatography/mass spectrometers) should be developed.

<u>Recommendation 8 (Science Instruments):</u> **OPAG recommends that NASA initiate a well-funded instrument development program that goes beyond the present low TRL instrument development programs. To prepare for future OP missions, NASA should establish a focused program that matures *in situ* and remote sensing instrument system concepts to TRL ≥ 6.**

6.0 SUMMARY

OPAG advocates a new focused technology effort as part of an OP Program in order to ensure readiness for launch of a mission to Titan and Enceladus in mid-2020s. Further, technologies that require long-term investment for missions beyond the next decade will be enabled and should also be considered. Table 2 shows a summary of the technologies required for specific missions.

Table 2. Summary of Technologies required for Outer Planet Missions

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

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