GLOBAL EXPLORATION ROADMAP CRITICAL TECHNOLOGY NEEDS

2019

International Space Exploration Coordination Group
Technology Working Group

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1. INTRODUCTION

Each step in expanding human presence beyond Low Earth Orbit (LEO) relies on the readiness of new capabilities and technologies (e.g., more powerful launchers, novel habitation modules with advanced life support, and vehicles with increased levels of autonomy). As no single agency has the resources to develop all those critical capabilities, appropriately leveraging global investments in technology development and demonstration is important. Although technology development is a competitive area, space agencies seek to inform their technology investment planning, create synergies and maximise their readiness to play a critical and visible part in the exploration endeavour.

International Space Exploration Coordination Group (ISECG) participating space agencies have identified a list of critical technologies related to the missions shown in the Global Exploration Roadmap (GER) that are currently not available or which need to be developed or matured. These technologies are considered technology “pulls” and can be mapped to corresponding agency technology development activities. This mapping allows a global technology gap assessment.

The current list of 47 technologies has been identified as being critical to advance the ISECG mission scenarios. It is building on a portfolio list of enabling critical technologies resulting from a human deep space exploration architecture analysis conducted by NASA and published in 2012.

The list of technologies presented in this document is maintained by the ISECG/ Technology Working Group (TWG) and updated based on the evolution of the GER mission scenario.

The purpose of this document is to share the GER Critical Technology list with global exploration stakeholders to inform the dialogue on priorities for technology development to enable the GER mission scenario.

Table 1-1 GER Critical Technology Portfolio Mapped to Exploration Destinations

Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
GER-003	LOX/Liquid Methane Cryogenic Propulsion System		🔴	🔵	🔴
GER-006	Electric Propulsion & Power Processing			🔵	
GER-007	Nuclear Thermal Propulsion (NTP) Engine			🔵	
GER-009	In Space Cryogenic Liquid Acquisition	🔵			🔴
GER-011	High Strength/Stiffness Deployable Solar Arrays for Surface Exploration		🔵		🔵
GER-012	Autonomously Deployable High Power In-Space Arrays			🔵	
GER-013	Fission Power for Surface Missions				🔵
GER-014	Multi-MWe Nuclear Power for Electric Propulsion (NEP)			🔵	
GER-015	Regenerative Fuel Cells		🔵		🔵
GER-017	Low Temperature and Long Life Batteries		🔴		🔵
GER-018	Precision Landing with Hazard Avoidance		🔴		🔴
GER-019	Telerobotic control of robotic systems with time delay	🔴	🔴	🔴	🔴
GER-020	Robots Working Side-by-Side with Suited Crew		🔴		🔴
GER-021	Autonomous Vehicle Systems Management	🔴	🔴	🔴	🔴
GER-022	Automated/Autonomous Rendezvous & Docking	🔴		🔴	
GER-023	Crew Autonomy beyond LEO	🔴	🔴	🔴	🔴
GER-025	High Data Rate Forward Link (Flight) Communications			🔴	🔴
GER-026	High Rate, Adaptive, Internetworked Proximity Communications			🔴	🔴
GER-027	In-Space Timing and Navigation for Autonomy			🔴	🔴
GER-028	High Data Rate Return Link (Hybrid Radio Frequency (RF)/Optical Comm)			🔴	🔴
GER-029	Closed-Loop Life Support Systems			🔴	🔴
GER-030	Enhanced Reliability Life Support Systems	🔴	🔴	🔴	🔴
GER-031	Deep Space Suit (Block 1)	🔴		🔴	
GER-032	Lunar Surface Space Suit (Block 2)		🔴		
GER-033	Mars Surface Space Suit (Block 3)				🔴
GER-034	Long Duration Spaceflight Medical Care			🔴	🔴
GER-035	Long-Duration Spaceflight Behavioral Health and Performance			🔴	🔴
GER-036	Microgravity Biomedical Counter-Measures for Long Duration Spaceflight			🔴	🔴
GER-037	Microgravity Biomedical Counter-Measures: Optimized Exercise Equipment			🔴	🔴
GER-038	Deep Space Mission Human Factors and Habitability			🔴	🔴

Ref. Number	GER Critical Technology (all)	Lunar Vicinity	Lunar Surface	Mars Vicinity	Mars Surface
GER-039	In-Flight Environmental Monitoring	🔴	🔴	🔴	🔴
GER-040	Fire Prevention, Detection & Suppression (reduced pressure)	🔴	🔴	🔴	🔴
GER-041	Space Radiation Protection – Galactic Cosmic Rays (GCR)			🔴	🔴
GER-042	Space Radiation Protection – Solar Particle Events (SPE)	🔴		🔴	🔴
GER-045	Mars In-Situ Resource Utilization (ISRU)		See Note 1		🔴
GER-047	Rapid Access Extra Vehicular Activity (EVA)		🔵	🔵	🔵
GER-048	Surface Mobility Systems		🔴		🔴
GER-049	Mission Control Automation beyond LEO			🔴	🔴
GER-050	Dust Mitigation		🔴		🔴
GER-051	Mars Entry, Descent, and Landing (EDL) Technologies for Heavy Payloads				🔴
GER-054	Inflatable: Structures & Materials for Inflatable Modules			🔵	🔵
GER-057	Low Temperature Mechanisms	🔴	🔴	🔵	
GER-062	In-Space Cryogenic Propellant Storage (Zero Boil Off LO2; Reduced/Zero Boil Off LH2)	🔴	🔴	🔴	🔴
GER-063	Thermal Control		🔴		🔴
GER-064	Robust Ablative Heat Shield (Beyond Lunar Return) - Thermal Protection System			🔵	🔵
GER-066	Long Duration Storage for Perishable Goods			🔴	🔴
GER-067	Solid Oxide Fuel Cell				🔵
Legend					
🔴	Technology development has been identified as Critical for currently baselined GER Mission Scenario Architecture (detailed in Section 2)				
🔵	Technology development is critical for options currently being considered in the GER Mission Scenario trade space (considered as Critical Alternative Technologies, detailed in Section 3)				

Note 1: GER-045 Mars In-Situ Resources Utilization (ISRU) - GER Critical Technology Portfolio does not include Lunar ISRU, deemed not critical within the current GER architecture. Ongoing ISRU gap assessments and IAWG review of human lunar surface architecture scenarios will inform future GER revision and GER Critical Technology Portfolio updates.

2. GER CRITICAL TECHNOLOGY PORTFOLIO

This section provides the following information for each of the identified GER Critical Technologies. Critical technologies are technologies identified as needing to be developed to meet the needs of the GER baseline mission architecture. Technologies which are already mature and available for use are not included in this list.

Description: Provides details on the technology, including the current state-of-the-art (SOA) or state of practice for space applications. This may include examples of international agency development efforts and/or rationale for why technology development is required to meet the needs of the GER mission scenario.

Performance characteristics: Objective of technology development. Details on what advancements beyond the current state-of-the-art are required, including metrics where known/applicable. All values shown are based on available data which has been reviewed and updated by the ISECG TWG team members, however all values should be considered as generic goals which may not represent specific use cases.

GER-003 – LOX/LIQUID METHANE CRYOGENIC PROPULSION SYSTEM

Description

An in-space stage, powered by a demonstrated workhorse engine, intended for boosting crew and cargo from LEO to destinations well beyond LEO. Lox/Methane has application for in-space propulsion systems such as service modules, landing or descent vehicles, and ascent stages. Lox/Methane propulsion can also be considered for access to space due to its low cost, high thrust and design of reusable engines for 1st stages of launchers, as well as re-ignitable engines for upper stages. This wide range of applicability should allow for some economy in the development of the required technologies. The fact that Lox is being used also allows for leveraging of existing technologies in many cases. The oxygen and methane propellant combination has the potential for good engine performance, which can result in lower vehicle mass and greater payload-carrying capability.

Performance Characteristics

- A throttleable regeneratively cooled pump-fed and/or pressure-fed engine to address gap for throttling (5:1 – 10:1), 360-365 second (sec), and for regenerative cooled engines in the 30 – 100 kiloNewtons (kN) range. Pump-fed solutions may be more size-efficient, and can provide additional options for throttling.
- 100 - 220 Newtons (N) Reaction Control System (RCS) thrusters with integrated cryogenic feed systems to address gap for thruster size/cost and then to evaluate Guidance & Navigation Control (GNC) impulse bit and thrust requirements.
- Long duration reliable cryogenic refrigeration systems capable of maintaining zero-boil-off and performing liquefaction of in-situ produced propellants (several hundred watts at ~90 Kelvin (K) (-183 Centigrade (C))).
- Composite cryogenic tanks with focus on spherical geometry to address gap in propellant tank technology.
- High performance pressurization systems that improve pressurant storage density and reduce mass to address gap for use with cryogenic propellants.

Notes / Comments

- This technology is considered critical for lunar and Mars surface missions, but Architectural Conditional (i.e. IAWG in-trade space) for Mars vicinity.
- ISECG/TWG performed a detailed gap assessment on Lox/Methane Propulsion with international Subject Matter Experts (SMEs).
- Further information and performance characteristics can be found in the "ISECG Lox/Methane Assessment Report" (Jan 2016).

GER-009 – IN SPACE CRYOGENIC LIQUID ACQUISITION

Description

Cryogenic liquid acquisition technology is needed for:

- unsettled tank-to-tank propellant transfer,
- unsettled tank-to-engine propellant transfer, and
- propellant transfer into heat exchangers needed to maintain propellant tanks at required temperature and pressure.

It is important to transfer only cryogenic liquids for these applications, without transferring ullage gas. Propulsive maneuvers can be used to settle the cryogens to ensure liquid-only transfer, but this parasitic propellant burn increases system mass, particularly for the frequent transfers needed for the thermodynamic vent system for tank pressure and temperature control. In micro- and reduced-gravity, liquid tends to cling to the walls of the tank, making it difficult to sufficiently cover the tank outlet during fluid outflow.

An in-space Liquid Acquisition Device (LAD) is required to acquire vapor-free liquid from a propellant tank in micro-gravity (g). LADs represent the first stage in successful fluid transfer from a tank to a propulsion system (or another tank). LADs rely on surface tension forces to separate liquid and vapor in the tank and capillary flow to maintain communication between liquid and the outlet during expulsion. A second system required for in-space liquid acquisition for large propellant storage and long duration missions is an autogenous pressurant system. Helium pressurant supply is impractical for these missions due to the helium mass required and the large launch mass penalty. An alternative to helium pressurization would be to extract a small amount of liquid or two phase fluid and feed it though a heat exchanger to vaporize the liquid and return it to the tank as a pressurant. These technologies are directly applicable to LO2/Methane propellant systems. LADs have a proven flight heritage when using higher surface tension storable liquids (e.g. hydrazine), but have not yet been tested in cryogenic liquids (Hydrogen (H) and Oxygen (O)) in low-g environments.

Performance Characteristics

- This technology is considered critical for Mars surface missions, but Architectural Conditional (i.e. IAWG in-trade space) for lunar vicinity.
- Ratio of LAD delivery system pressure drop to Bubble Pressure Point (BPP) drop at maximum outflow rate: < 0.75 to 0.5
- % of LAD residual LH2 mass to total tank LH2 mass (Expulsion efficiency): < 1% to 3%
- Ratio of total autogenous pressurant system mass to the mass of equivalent helium pressurant system: < 0.8 to 1.0

GER-017 – LOW TEMPERATURE AND LONG LIFE BATTERIES

Description

Long life and low temperature survivable batteries will enable Lunar night survival and operations. Polar Crater Operations will require batteries that can survive and operate in a cryogenic thermal environment.

Recent advances driven by terrestrial applications have produced batteries with high energy density, however the performance in cold temperatures is significantly degraded, often requiring power to be diverted to maintain temperature control of the battery pack for peak operating efficiency, requiring bigger batteries with more mass. Additionally, recharging a battery at extreme temperatures can reduce the life of some types of batteries, such as Lithium (Li)-ion batteries. Batteries that can operate (discharge and recharge) at low temperatures are required in order to reduce mass, save power and increase mission duration.

Performance Characteristics

The following capabilities are recommended targets:

- Battery-level specific energy > 220 Watt-hour (Wh)/kilogram (kg) and energy density > 410 Wh/liter at a C/10 discharge rate at lunar night temperatures (-180 C).
- Lifetime of at least 15 years with < 90% degradation (TBC), assuming contiguous 14 day/night lunar cycles.
- Operate in a Perennially Shadowed Region such as a polar crater for 14 days.

Notes / Comments

- This technology is considered critical for lunar surface missions, but Architectural Conditional (i.e. IAWG in-trade space) for Mars surface.
- For Mars missions, even if the baseline power generation is likely to be nuclear, the need for batteries will be expected as power demand fluctuates while the nuclear power source will be generating limited and maybe relatively constant power.
- Terrestrial applications are advancing rapidly in this area and may provide Commercial Off-The-Shelf (COTS) solutions for future missions.

GER-018 – PRECISION LANDING WITH HAZARD AVOIDANCE

Description

Autonomous landing and hazard avoidance systems required in support of the GER mission scenario, including terrain relative navigation, that operate in all lighting conditions, including darkness. Autonomous landing and hazard avoidance technology would enable lunar, Near Earth Orbit (NEO), Mars moons, and Mars surface missions requiring precision landing, including repeat destinations for campaign missions.

The proximity manoeuvres between a spacecraft and the landing surface, are considered critical from the point of view of the GNC operations. In order to find and track the surface object, maintain stabilized orbits or perform landing and touchdown operations the spacecraft needs to rely on different optical sensors. These optical sensors acquire different type information from the target in order to enable the different GNC operations. Such imaging sensors are able to measure, with high precision, the distance of the spacecraft from the surface of the surface object. In addition to the topographic profile, from which the global shape model can be produced, these sensors can be also used to determine the reflectivity of the surface, as well as the slope and surface roughness.

An accurate navigation is needed to correctly guide the spacecraft in its descent and touch-and-go trajectory towards the surface object. The optical sensors are able to perform autonomous vision-based navigation using feature landmark recognition. Image-processing and navigation algorithms are developed to perform vision-based navigation around and towards the surface object.

Performance Characteristics

- The components and techniques have been simulated and tested at breadboard level but a full set of integrated field tests is needed to show Technology Readiness Level (TRL) 6 and applicability to future missions.
- Need 90m accuracy at 3-sigma uncertainty relative to pre-mission identified landing location. Need 0.3m (rock diameter) hazard recognition and avoidance as horizontal ground resolution.

Notes / Comments

- Assumes a scaled ground demo or hardware-in-the-loop operation validation using image stimulation techniques with high fidelity.

GER-019 – TELEROBOTIC CONTROL OF ROBOTIC SYSTEMS WITH TIME DELAY

Description

Telerobotic operations enable astronauts or ground operators to remotely command or operate robots (including but not limited to rovers and/or manipulators) at near or remote destinations. The operators send commands (for example: motion and/or force commands) to execute a task. The operator may receive visual, force/moment, or other feedback through a time-delayed telecommunication and control network where no direct physical contact exists between the operator and the robot. Enabling distributed operations where Earth-based ground controllers and/or astronauts can remotely operate robotic systems safely and efficiently in dynamic environments beyond LEO will alleviate crew workloads and allow for efficient operations when on-orbit or in-situ crew are not available.

Current on-orbit telerobotic operations with time delays of 2 to 10 seconds include dexterous payload handling and contact operations for robotics on board the ISS. This includes ground controlled operations for external payload maneuvering; berthing with time delays (e.g. H-II Transfer Vehicle (HTV) 6 berthing and Orbital Replacement Unit (ORU) payload transfers by Special Purpose Dexterous Manipulator (SPDM or Dextre) or Japanese Experiment Module Remote Manipulator System (JEMRMS)) as well as demonstrations of terrestrial robots commanded from the ISS with time delays of 2 seconds or less. The state of practice for long time delays is a single command sequence per day of a slow ground robot in a static environment without human intervention in real time (e.g., Mars Exploration Rovers driving an average of 100 meters (m)/day).

Performance Characteristics

Based on the 2018 Gap Assessment the following improvements are recommended for improved performance:

- High-speed space-qualified processors to support increased performance in all telerobotic functions, as well as enabling visual servoing for fine alignment and advanced onboard planning for hazard avoidance. In order to improve the controlled system bandwidth for advanced systems there is an inherent need for high-speed, low-latency data buses.
- Performance improvements in Light Detection and Ranging (LIDAR) systems in areas related to detector pixel density, compactness, power efficiency and reliability.
- Cameras that can localize targets under any lighting scenario and space-qualified LIDAR systems with improved target detection for visual servoing and auto alignment.
- New tools for Validation and Verification (V&V) of autonomous systems is needed to minimize the risk of incorrect decisions or behaviour on the part of the autonomous controller, particularly for cases where extensive pre-flight testing under representative conditions is not possible.
- In order to reduce cost, schedule and risk, International standards for robotic interfaces need to be developed for orbital and surface operations.
- Improved relative navigation without using Global Positioning System (GPS).
- Improved sensing and corresponding telemetry are needed to better represent actual conditions and items that cannot be seen through a camera, such as soil properties from a distance.
- High-bandwidth (3 Megabits per second (Mbps) or greater) deep space communications link to allow for data required for telepresence to be transmitted.

For complete details please refer to the "Telerobotics control of systems with Time Delay Gap Assessment Report"(2018), available on the ISECG TWG website.

GER-020 – ROBOTS WORKING SIDE-BY-SIDE WITH SUITED CREW

Description

Human mission activities can be performed more effectively if robotically assisted. Coordinated efforts between humans and machines/robots can improve the mission risk/productivity trade space. The top technical challenges in human-robot interactions are multi-sensor feedback, understanding and expressing intent between humans and robots, and supervised autonomy of dynamic/contact tasks. When robots and humans need to work in close proximity, sensing, planning, and autonomous control system for the robots, and overall operational procedures for robots and humans, will have to be designed to ensure human safety around robots. The goal is to enable EVA crew and machine interaction without real-time control and support from Intra-Vehicular Activity (IVA) or ground control personnel.

Currently, robotics are commonly used to assist crew during and EVA on board the ISS. The robots are usually controlled by an astronaut inside the ISS in communication with the EVA crew member. Occasionally ground control operators may operate the robots for payload hand-offs however this is typically avoided due to the potential loss of communications in a time critical scenario. Allowing the EVA to directly control the robotic manipulators could increase safety and simplify the operations for crew.

Performance Characteristics

Overcome limits of state-of-the-art with foundation work:

- Develop operational concepts that allow for EVA control and interaction with robots with no reliance on Ground and/or IVA support for monitoring and control of robots in proximity to EVA crew.
- Develop international common standards and safety protocols to ensure that automated robots interact safely with humans and provide resilience to human errors. This includes defining keep-out zones, maximum loads and rates for operations in proximity to humans as well as protocols for transferring control to/from automatic modes or remote teleoperation to EVA control.
- Create and test multi-modal human-robot interfaces that are compatible with suited crew and autonomy software.
- Develop international standards for V&V of autonomous control systems to ensure the safety of the human-robot interaction.

GER-021 – AUTONOMOUS VEHICLE SYSTEMS MANAGEMENT

Description

Enables autonomous vehicle management with limited crew effort and little to no ground oversight. This autonomous capability is required to ensure safe vehicle operations and monitoring of complex systems, especially at increased distances from Earth where communications time delays are present.

Currently many crewed space vehicles, such as the ISS, rely heavily on ground support for routine systems management and control of critical systems such as power management and GNC. Transferring these tasks to the crew is not feasible due to the workload. Automation is required to minimize crew time required on system maintenance while ensuring safety. Currently, automating on-board systems is limited in part by space-certified computer processing capabilities.

For un-crewed vehicles, such as rovers, time delays limit the efficiency of a vehicle; for example, a Mars rover that is reliant on commands from the ground to proceed with a command sequence may become trapped in a region where communication is not possible. Currently, automating on-board systems is limited in part by space-certified computer processing capabilities.

Additionally, for spacecraft/element(s) that will not have permanent human presence, the capability for complete autonomy will be required (including utilization of robotic caretakers).

Hazard assessment is highly critical when required for human-rated vehicles. While it is currently applied in different ways, more complex missions and vehicles will require higher levels of abstraction which will also benefit from more advanced model understanding.

Due to eclipses, solar conjunctions or natural elements of orbits there is no direct communications to Earth and therefore signal interruptions will occur. The disruptions are highly dependent on the type of mission. Some examples are:

- Solar conjunctions on Mars can disrupt communications up to two weeks.
- Communications with the Gateway may be impacted by occlusions depending on the orbit.
- Lunar missions landing on the dark side of the Moon have no direct communications to Earth, i.e. rely on orbiter communication capabilities.

Performance Characteristics

- Enable on-board vehicle systems management for mission critical functions at destinations with > 3 second time delay.
- Enable autonomous nominal operations and Failure Detection Isolation and Recovery (FDIR) for crewed and un-crewed systems.
- For un-crewed vehicles develop on-board decision-making capability to allow operations to continue through task completion without human intervention.
- Reduce on-board crew time to sustain and manage vehicle/habitat by factor of 2x at destinations with > 6 second time delay (see GER-023 – Crew Autonomy Beyond LEO).
- Significantly reduce Earth-based mission ops requirements for distant mission support delay (see GER-049 – Mission Control Automation Beyond LEO).
- Enable planning and execution on-board, with identification of the current state of the environment and space system (including possible science opportunities).

- Requires advancement in space-qualified high-speed processors.
- Incorporation of data fusion techniques, complemented if required by artificial intelligence tools (data mining, pattern matching, etc.) needs to be further developed. In addition, reasoning and understanding the consequences of a given state in support of forecasting and planning.
- Automated reasoning (Constraint Satisfaction Problems, Rule Engines, Model checking, Machine learning, etc.) are some of the techniques to be further investigated in the context of space qualified systems (lacking behind their terrestrial counterparts).
- Advancements in motion planning are required, referring to both vehicle (orbital and surface) path planning, and libs (such as robotic arms) trajectory planning, being all of them highly dependent on the underlying platform architecture.

Notes / Comments

- ISECG/TWG performed a detailed gap assessment of Autonomous Systems with international subject matter experts (covering subject material from GER-021, GER-023, and GER-049).
- Further information and performance characteristics can be found in the "ISECG Autonomous Systems GAP Assessment Report".
- Per the GAT report, additional cross-cutting technology challenges applicable to Autonomous Systems include:
    - Communications; While a critical gap is not identified, the speeds and bandwidths needed to support autonomy and the evolution from Earth-based mission operations to mission operations based at distant destination are not well understood.
    - Cyber-Security; Ensuring the security of our cyber resources is vital to ensuring capabilities for autonomy capability are not compromised.
    - Radiation Protection; Critical gaps in the protection of humans, live food sources, and electronics from the effects of harmful radiation are well-known and are the focus of numerous studies and investigations within partner agencies.
    - Trusted Autonomy; Until these gaps are overcome, safeguards should be in place to allow human or automated intervention. Guidelines on when and how to invoke that intervention are also needed.
    - Verification & Validation; There is critical gap in automated methods for V&V, which results in a critical gap in the ability to perform low-cost, verification and validation of software that model certification/accreditation for use in decision-making.

GER-022 – AUTONOMOUS RENDEZVOUS & DOCKING

Description

The space industry has yet to develop and demonstrate a robust Autonomous Rendezvous and Docking (AR&D) capability suite, including proximity operations and target relative navigation, that can be confidently utilized on human spaceflight and/or robotic vehicles over a variety of design reference missions and for the whole operation range (autonomous in-flight validation has been performed in the scope of the Automated Transfer Vehicle (ATV) missions to the ISS, only during the last mission phase at short ranges). Rendezvous missions include flybys of destinations without landing or docking. Proximity operations require loiter at destinations with zero relative velocity. Major challenges include the ability to rendezvous and dock in all ranges of lighting, work across near to far range, and achieve a docked state in all cases. The benefit of this technology development is to improve human safety, improve mission performance and flexibility by enabling autonomous rendezvous and proximity operations interactions with complex or uncontrolled planetary bodies.

The capability of being autonomous refers to a system capable of sensing its environment and making self-decisions on its navigation, with only high-level commands needed. An automated system is not capable of making its own decisions, and merely executes a set of pre-defined instructions without requiring any real-time human control.

In order to achieve an autonomous capability, several technologies are needed; some of them are currently under development.

Performance Characteristics

- System performance driven by the need for autonomous operations; high reliability, rapid missionization, rendezvous with non-cooperative targets with unknown geometry, tumbling attitude, and unknown surface features, and mass/power constraints.
- Maturation to a broad environmental scenario of subsystem technologies (relative navigation sensors, GNC flight software, system managers, and mechanisms) and integrated end-to-end system validation for the whole autonomous operation range), to accomplish autonomous rendezvous and proximity operations for various in-space spacecraft docking operations required for the GER mission.
- Resolution requirements that meet or exceed the requirements given in the International Rendezvous System Interoperability Standard (IRSIS).

Notes / Comments

- Assumes Scaled ground demo or hardware-in-the-loop operation validation using image stimulation techniques with high-fidelity.

GER-023 – CREW AUTONOMY BEYOND LEO

Description

Autonomous crew operations (planning, commanding, fault recovery, maintenance) for Beyond LEO missions is essential to accommodate the ground communication delays and blackouts at distant locations. Current human space flight missions have a heavy reliance on ground support for non-time critical decision making, especially in off-nominal scenarios. Systems and tools need to be developed to provide the crew with independence from Earth-based ground operations support in decision making, in particular when dealing with anomalies.

An important aspect of crew autonomy is to ensure that the crew is in good health, where health includes their state of physical, mental and social well-being. In order to stay healthy, the crew needs to be able to autonomously monitor their health, perceive any deviations from the baseline, analyze and diagnose the reason for the issue and then act (monitor, apply countermeasure, or treat).

Crew performance in directly related to crew health, where any deviations from the baseline condition will affect the performance of any operational tasks conducted by the astronaut. (see also GER-035 – Long-Duration Spaceflight Behavioral Health and Performance)

Food production for crew consumption, along with water and air loop closure is essential to expanding and sustaining the human presence beyond LEO. Development and testing of open, partially open, and closed looped plant growth systems has shown great progress in Earth-based experiments. (see also GER-066 – Long Duration Storage for Perishable Goods)

Crew Safety & Intervention; The functions of the crew safety must be maintained and must not be lost during the flights and missions. The system should provide the capabilities to avoid the catastrophic hazard condition which may cause the personal injury or fatality.

Stowage Management; the capability to correctly stow items, trace their positions within the spacecraft, avoid incompatibilities that can harm them (i.e. hard drives stored close to magnets), and validate loading and unloading procedures becomes a key factor for the success of long-duration exploration endeavors.

Performance Characteristics

- Automate 90% of nominal operations for vehicles or habitats at destinations with > 6 second time delay to ground.
- Enable coordinated ground and crew nominal operations at destinations with > 6 second time delay (see GER-049 – Mission Control Automation).
- Provide automated tools for crew to make real time decisions in off-nominal situations based on real-time data.
- Enable automatic detection of off-nominal situations and automatically recover or enable crew to put vehicle/habitat in safe configuration without ground coordination or assistance.
- Crew Medical; critical gaps have been identified in baseline modeling, diagnostic support, medications, training, and treatment.*
- Food Production; critical gaps have been identified in sensor technologies, model building, anomaly & fault detection, radiation & microorganism hazards, and autonomous planting/harvesting/food processing in a microgravity environment.*
- Crew Safety & Intervention; further advancements in caution & warning, diagnosis & prognosis of systems, fault response, and actuation (balance between autonomous and manual intervention).*
- Stowage Management; advancements in autonomous logistics records, storage/packaging, locating & recovery are required.*

Notes / Comments

- ISECG/TWG performed a detailed gap assessment of Autonomous Systems with international subject matter experts (covering subject material from GER-021, GER-023, and GER-049).
- Per the GAT report, additional cross-cutting technology challenges applicable to Autonomous Systems were identified (see also GER-021 – Autonomous Vehicle Systems Management).

*Further information and performance characteristics can be found in the "ISECG Autonomous Systems GAP Assessment Report".

GER-025 – HIGH DATA RATE FORWARD LINK (FLIGHT) COMMUNICATIONS

Description

High data rate forward links can be realised by RF and optical transmissions. High rate RF forward links beyond current single antenna capabilities require uplink arraying of multiple antennas. The development of arrayed ground station transmitters from arrayed antennas has the capacity to produce uplink data rates significantly higher than current Space Network (SN), Near Earth Network (NEN), Deep Space Network (DSN) capabilities to improve the link budget and either increase data rates for uplinked video, imagery and critical software or reduce spacecraft antenna size and accommodation requirements. Increased uplink power therefore has the advantage of reducing the communications payload mass in space with spin off effects for guidance, navigation and control in terms of weight and power. Higher uplink power also has the potential for improved orbit determination accuracy and trajectory management.

High rate optical forward links in accordance with the optical High Photon Efficiency (HPE) standard can be realised by using photon counting receivers onboard with an associated high rate modem, and using kW Laser transmitters on ground, that are anyway needed for the pointing, acquisition and tracking of the onboard terminal. Optical links can also be used for mm-accuracy ranging measurements. Orbital optical relay terminal(s) may allow extension of link distances and modular growth to communications networks.

Performance Characteristics

- Enable uplink rates: 25-50 Mbps at 1 Astronomical Unit (AU) using X-band
- Size and weight reduction: compared to currently achievable receiver: > 50 %
- Leverage navigation improvements in orbit determination accuracy and trajectory management from improved communication link.
- Optical forward links using HPE were demonstrated to Lunar distance up to 20 Mbps (NASA LADEE 2013). By appropriate scaling of the ground and on-board systems, communications with Mars would be possible beyond 50Mbps.
- High performance onboard photon counting receivers with associated modems would in principle allow to go up to 2.1 Gbps, which is the limit of the current standard.

Notes / Comments

- Ensuring phase coherency for arrayed uplink transmitters is difficult and more so as the frequency increases from S, X, and K band upwards.
- X-band and Ka-band are known technologies and do not need not be considered critical to develop anymore.
- Respective transmitters, covering a distance of 1 AU, probably do not need to be developed anymore. However, the orientation accuracy and/or size of antennas still need to be improved.

GER-026 – HIGH RATE, ADAPTIVE, INTERNETWORKED PROXIMITY COMMUNICATIONS

Description

Enable high data rate communications between multiple in-space elements through an automated adaptive protocol similar to a plug and play concept (cognitive radio). This has the capacity to:

1) form automated networks in space between autonomous systems for improved situational awareness;
2) sense RF conditions and adapt autonomously;
3) enable elements to store, forward, and relay/route information to other elements intelligently when communications is available by using standard Disruption Tolerant Networking (DTN) techniques at the required data rates;
4) enable communication elements to be reprogrammed from ground based or in-situ systems. The benefit of this technology development is to create automated networks and improve situational awareness and communications, improving operational efficiency.

Performance Characteristics

- Data rate: > 20 Mbps simultaneously between peers
- Employ multiple frequency/modulation/coding/power schemes, including low frequency schemes to enable low rate, non-line of sight communication through small NEOs when relay through other elements is not available. (Max range: < 20km. Max NEO size for penetration: < 50 m.)
- Max storage time: < 5 min/Element@ 20 Mbps, Max routing: < 20 destinations/Element
- Enable radios to be adapted in frequency of operation, modulation and coding to information as it is discovered about the NEO environment in near real-time. (Near real-time: < 30 minutes of each NEO characterization performed by in-space elements.)

Notes / Comments

- Today's mobile systems technologies (4G, 5G) basically offer suitable technologies and solutions. On a smaller scale, systems similar to adaptive WIFI or the military link 16 concept may also be applicable.

GER-027 – IN-SPACE TIMING AND NAVIGATION FOR AUTONOMY

Description

Enable elements to perform independent navigation during complex in-space maneuvers; enable precision required for absolute and relative navigation for in-space elements; enable increased element onboard reference timing generation, timekeeping, distribution and inter-element synchronization to eliminate dependence on Earth-based systems. The benefit of this technology development is to improve situational awareness and communications, improving operational efficiency. High-precision timekeeping significantly reduces accumulated navigation error over long periods of time, enabling mission autonomy for long periods of time without synchronization events with ground or other (X-ray, etc.) synchronization.

Performance Characteristics

- Complex maneuvers: navigating amongst multiple in-space elements plus 1-3 NEO objects in dynamic motion in proximity to elements
- Absolute position required for navigation: < 0.4 m. Relative position required for navigation: < 0.4 m
- This requires space-qualified clocks that are 10x-100x more stable than existing space qualified clocks. (Element timekeeping accuracy required: milliseconds to nanoseconds depending on mission.)
- To some degree artificial intelligence (“mission intelligence”) will be required in order to process and combine all sensor data and to be able to take autonomous decisions for the continuation of the mission.

GER-028 – HIGH DATA RATE RETURN LINK (HYBRID RF/OPTICAL COMM)

Description

This technology provides the capability to perform four functions with a single system: RF and optical communication, optical ranging and RF imaging. The optical components have the capacity to provide Gigabits per second (Gbps) data rates to allow very high data rates between space elements and ground stations. This has the capacity to significantly increase link budgets and reduce the size and mass of space communications payloads with the spin off for reduced guidance, navigation and control systems through combined RF/Optical capability in a single system. A hybrid RF/optical capability would allow multiple spacecraft to communicate within the same ground aperture. This would relieve ground antenna capacity and scheduling issues on the Earth side; enable reliable high data rate communications between in-space elements and ground, and provide efficiencies in power and providing simultaneous RF beacon capabilities while the optical system is operating. This is a recommended technology for missions where both imaging and long-range, high rate communications are required for the mission.

Performance Characteristics

- Power savings during optical mode: < TBD Watts
- Size and weight reduction compared to dual systems: < 40 %
- Optical data rate to 0.5 AU from Earth: > 1 Gbps simultaneous Upload (U/L) and Download (D/L) with ground.
- Near Earth Objects (NEOs) at 0.5 AU distance or greater, including Mars missions.

Notes / Comments

- Required RF and free space optical communication technologies are already available today. However, they need to be adjusted to the new distances (stronger lasers, bigger telescopes).
- The DSN is developing a hybrid RF optical system on it beam waveguide antennas. The first rollout will be before 2025. Gateway is also considering an optical communication technology demonstration.
- The recently standardised High Photon Efficiency (HPE) communication allows for data rates up to 2.1 Gbps. First optical systems following this standard are under development.

GER-029 – CLOSED-LOOP LIFE SUPPORT SYSTEMS

Description

Long-term beyond LEO exploration missions will ask for closed-loop Life Support Systems. In particular, the currently utilised systems will not meet the stringent requirements associated to a Mars Exploration campaign. Building on the systems developed for LEO and near-term beyond-LEO applications (i.e. lunar vicinity and lunar surface) and applying the lessons learned while developing them, the next generation closed-loop Life Support Systems will be developed. Research activities will focus on enhancing and developing new, flexible Environmental Control and Life Support (ECLS) technologies and systems to increase system closure and reduce logistics, enabling autonomous long duration human exploration missions. Based on systems analysis and trade studies, targeted functions and technologies should include:

- Atmosphere Revitalization (AR) loop closure by furthering O2 recovery, and reducing logistics. Technologies may include Bosch, methane processing, and solid oxide electrolysis as well as advanced trace contaminant control and filtration.
- Water Recovery (WR) loop further closure by processing brines. Reduce clothing logistics and enhance crew health by enabling water recovery from laundry and hygiene wastewaters, respectively. May also include purification of water derived from ISRU sources.
- Solid Waste Processing (SWP) to recover water, reduce volume, and stabilize for long term storage. Technologies include compaction, drying and mineralization of solid wastes, including trash, feces and solid by-products from AR and WR processes.
- Opportunities to develop common technologies, processes, and components suitable for multiple vehicles and missions.

Performance Characteristics

The following targets are recommended:

- Approach 100% closure for water and oxygen. Enable vehicle and mission autonomy through high reliability, reduced dependency on logistics, and consumable mass, and lower launch and mission costs.
- Meet new vehicle requirements including high reliability, operation in more extreme cabin environments (reduced pressure [55 kilopascal (kPa) (8 pounds per square inch absolute (psia))] and elevated O2 [>32%]), reclamation of more complex process streams, and planetary protection.
- Bring technologies to TRL 6 through progressive levels of ground-based integrated testing and ISS flight demonstrations. Perform long duration human-in-the-loop testing to flush out hardware closed-loop issues such as contaminant build-up.
- Implement systems' automated failure detection capabilities (in close relation with GER-021, through systems' self-analysis functions and data analytics tools).

Notes / Comments

- A long term exploration strategy will also require investment in regenerative life support technologies. Besides physico-chemical processes to retrieve oxygen from CO2 in the cabin air, biological and biochemical processes have the potential to not only recycle oxygen and water, but as well to retrieve other vital elements (e.g. C, N) and provide food, hence dramatically reducing the needed upload mass.

GER-030 – ENHANCED RELIABILITY LIFE SUPPORT SYSTEMS

Description

Near-term beyond LEO exploration missions will ask for Life Support Systems having enhanced performance and reliability with respect to the ones currently used on-board the ISS (e.g. N_2 recovery, O_2 tanks recharge for longer EVA). Without such improvements, much of the current systems will not work or would require too many consumables. Nevertheless, programmatic aspects call for an enhancement of already existing technologies or systems instead of completely new developments.

For Moon and Mars missions, the need for waste reduction will become acute as the cost of any mass of waste returned to Earth will be exorbitant, and it is expected that permanent waste storage will be very unpopular. A full recycling of waste should be the ultimate goal (e.g. re-using material for construction or parts).

Spares for redundancy and repair will become one of the sizing elements for deep spaceflight beyond the Moon. Once on a Mars trajectory there is no U-turn possible. Additive manufacturing is a very good answer to this challenge, as well as circular systems (waste/materials).

As an analogue and for technology validation, synergies can be found with inland Antarctic research stations where the waste challenges are identical to deep space missions.

Research activities will focus on:

- Improving performance and reliability of existing open and closed-loop Environmental Control and Life Support Systems (ECLSS), including Atmosphere Revitalization (AR), Water Recovery (WR), Waste Management and Crew Accommodations, in order to reduce logistics over the state-of-the-art.
- Performing systems analysis and trade studies to correctly select applicable technologies. Deliver new gap-filling technologies identified by vehicle elements including common adjustable pressure regulator capable of controlling a range of cabin, suit loop, and EVA suit pressures, low maintenance human waste collector and trash compactor, clothing, washer and dryer.
- Perform long duration testing to address hardware reliability issues.

Performance Characteristics

Meet or exceed performance over current state of the practice (90% recovery of water from urine and humidity condensate, and >50% of O2 from CO2). Meet new vehicle element requirements:

- More robust and reliable components (e.g. compressors, fans, separators, vacuum pumps, sensors) to support longer (unmanned) loiter and extended mission durations that withstand the launch/landing loads environments and thermal/dust environments.
- Increased vehicle autonomy, high reliability, reduced logistics and in-flight reparability.
- Possibly more extreme cabin environmental conditions (i.e., reduced pressure [55 kPa] and elevated O2 [>32%]).
- Possibly more complex process streams for recycling (wastewater from trash, hygiene and laundry).
- Increased systems' automated failure detection capabilities (in close relation with GER-021, through systems' self-analysis functions and data analytics tools).

GER-031 – DEEP SPACE SUIT (BLOCK 1)

Description

EVA suit with rear entry capability and crew-cabin pressure matching for compatibility with reduced pressure; improved life support systems for increased life, reliability, and flexibility; and improved power-avionics-software to increase crew autonomy and work efficiency.

High Specific Energy Batteries with very high specific energy and energy density are required to enable untethered EVA missions lasting 8 hours within strict mass and volume limitations. Batteries are expected to provide sufficient power for life support and communications systems, and tools including video and lighting.

Performance Characteristics

- Deep Space Suit capable of operations at ~55 kilopascal differential (kPaD) (8 pounds per square inch differential (psid)) (state-of-the-art is 29.6 kPaD (4.3 psid)).
  - Gateway needs: Dexterous gloves for IVA contingency repairs while the cabin is depressurized. Experience shows that EVA repair inside a cabin is not practical (suits are too bulky), but IVA suited repair may be possible, if gloves are flexible enough for fine motor skill work when suit is pressurized.
- Portable Life Support System (PLSS):
  - Variable set-point oxygen regulator provides more flexibility for interfacing with multiple vehicles, the ability to start an EVA at a 55 kPaD (8 psid) pressure differential driven by a suitport and then decrease pressure mid-EVA for improved mobility, and to treat decompression sickness in the suit (variable between 0 and 62 kPaD (9 psid)).
  - On-back regenerable CO_2 and humidity control (eliminates consumables).
  - Robust water loop that can handle low quality water, long duration missions, low pressure operations, and bubbles (> 50 EVA life).
- Power-Avionics-Software (PAS):
  - Compatible with high specific energy battery (> 235 kW-hr/kg).
  - Assumed battery development is provided externally to EVA development projects.
- Batteries: Battery-level specific energy > 325 Wh/kg and energy density > 540 Wh/liter. 8 hour operation per mission over an operating temperature of 2 to 50 degrees C. Nominally 100 cycles and 5 year calendar life. Control of the thermal runaway hazard which would reduce the system packaging to control the hazard.
  - Note: While this technology is specific to EVA needs, advanced batteries are an enhancement technology for every type of powered system.
- Radio that is network capable for missions involving multiple assets (vehicles and suits) and has data rates that support transmitting high definition video (> 10 Mbps).
- EVA display (either helmet mounted or handheld) that improves upon the 12 character Liquid Crystal Display (LCD) and laminated flip cards used on ISS.
- EVA information system that increases crew autonomy and work efficiency.

GER-032 – LUNAR SURFACE SPACE SUIT (BLOCK 2)

Description

EVA suit for use at surface destinations with small gravity field and hard vacuum atmosphere (e.g. Lunar surface).

Applications:

- EVA operations on the Lunar surface.
- Pressurized rover concept of operations with airlock-enabled ingress.

Performance Characteristics

The assumption is that Block 2 development occurs after Block 1 (deep space suit) and that Block 1 development is successful and technologies can be transferred to Block 2 as appropriate. Technical changes from Block 1 to Block 2:

- Suit: improved lower torso mobility, upgrade to dust tolerant garments and joints.
- Portable Life Support System (PLSS): upgrade to dust tolerant components (quick disconnects, relief valves, etc).
- Power-Avionics-Software (PAS): upgrade to dust tolerant electrical connectors, switches, and controls; increase the capabilities of the information system for additional autonomy; take advantage of advances in battery or avionics components as appropriate.

GER-033 – MARS SURFACE SPACE SUIT (BLOCK 3)

Description

Suitport-compatible EVA suit for surface destinations with intermediate gravity field (1/3 g) and low pressure atmosphere (Mars).

Critical open questions include resolving the knowledge gap regarding what life signatures are leaking/venting from current EVA systems and determining how long would those organisms survive in the Mars surface environment.

Performance Characteristics

Assumes Block 3 development occurs after Block 1 (Deep Space Suit) and Block 2 (Lunar Surface Suit).

Technical changes from Block 2 to Block 3:

- All EVA systems components have an increased need for decreased mass.
- Suit: additional emphasis on boots, thermal insulation for CO_2 atmosphere.
- PLSS: Evaluate existing technologies for use in CO_2 atmosphere, may need to develop a new PLSS schematic.
- PAS: increase the capabilities of the information system for additional autonomy (even bigger time delay); take advantage of advances in battery or avionics components as appropriate.

Notes / Comments

- Compatibility with Rapid access EVA Suitport is in ISECG Architecture Working Group (IAWG) trade-space for Mars surface operations. (See GER-047 – Rapid Access EVA)

GER-034 – LONG DURATION SPACEFLIGHT MEDICAL CARE

Description

Strong evidence from spaceflight and analogs indicate that medical conditions of different complexity, severity, and emergency will inevitably occur during long-term Exploration missions. Long duration missions (>1 year) increase the risk of serious medical conditions due to limited options for return to Earth, no resupply, highly limited mass, volume and some communication delays. Plans for medical care consider the most likely medical conditions, their operational and health consequences and the resources needed for treatment. Plans for the medical system seek to minimize the probability of mission failure or loss of crew.

The health of astronauts in space may be compromised by both acute (environmental, injury, trauma) and chronic medical conditions (medical illnesses), the former of which may strike unexpectedly and at any time (*e.g.* an infection), whilst the latter will develop over longer periods of time. Key to managing both during future human space exploration missions will be the ability to diagnose and treat, and to do so within the constraints of space vehicles/habitats and mission scenarios. As on Earth, diagnosis will be a combination of patient history and physical examination, including diagnostic tests, and will rely on both the skill of the examiner and the quality/variety of diagnostic testing equipment available. Likewise, treatment of both acute and chronic medical conditions will require a combination of crew knowledge, skill and treatment 'technologies', including medications, instruments and hardware.

To achieve this will require a paradigm shift in medical care, from the current 'advisor' (ground) / 'client' (crew) approach to an integrated 'system' approach, in which the day-to-day burden of responsibility shifts from the ground to the vehicle. As such, the vehicle, medical system and crew all contribute to decision-making and task execution and thus, radically increasing autonomy, flexibility and responsiveness. This paradigm shift will be based around the identification of the medical conditions most likely to occur during exploration missions (*e.g.* NASA's Integrated Medical Model [IMM] Medical Conditions List) and the provision of knowledge and training (and skill maintenance), and technologies that, in different proportions, will allow the majority, if not all, of the identified medical conditions to be managed by the crew. The medical system must monitor and treat crewmembers during the mission. The requirements for the medical system are impacted by mission duration; number of EVAs; age and gender of the crew; and crew medical expertise. ISS and flight analog environments have to be fully exploited to test and validate the future technologies for the medical care kits and associated technologies.

Performance Characteristics

The required performances will depend on the defined accepted risk for the targeted mission scenario. The expected performances are to support the crew for maintenance of their health and for autonomous management of health events. This includes providing support for monitoring, diagnostic, treatment and care. This includes as well support for the crew selection and for the medical training or medical knowledge maintenance. The related technologies shall thus support:

- Training of the crew for medical aspects (pre-flight and in-flight), for instance with access to knowledge bases and with augmented or virtual reality tools.
- Continuous monitoring of the health of the crew, in particular to monitor the physiological disorders due to the space environment (e.g. bone or muscle loss, cardiovascular changes, intracranial pressure, renal stones) including with imaging techniques, laboratory analyses.
- Diagnostic support.

- Treatment and care support.
- Decision support for management of medical events. The technologies may include platforms integrating multiple diagnostic and therapeutic smart medical devices, focusing on early detection and intervention of high-consequence and remediable conditions, with consideration for dual-use technologies.
- Capabilities include non-exhaustively: diagnostic imaging, oxygen concentrator, ventilator, laboratory analysis (saliva, blood, urine), bone fracture stabilization and healing, medical suction, rapid vascular access, dental care, kidney stone diagnosis and treatment, intravenous (IV) solution preparation and delivery, medical consumables inventory tracking, computer aided diagnostic, rapid diagnostic tools, assistive and guidance techniques, medical data management and expert systems to support decision-making.

GER-035 – LONG-DURATION SPACEFLIGHT BEHAVIORAL HEALTH AND PERFORMANCE

Description

Behavioral health and interpersonal relations among crewmembers are critical to the success of long duration exploration missions in isolated, confined and extreme environments. This recognition, although difficult to precisely quantify, is shared by science advisory groups, congress, the general public, and most importantly, astronauts. Technologies are required for crew selection and composition, training, support, monitoring, and intervention. Based on terrestrial analogues, the probability of an adverse behavioral health event is 2% and 5% for 3-month and 6-month missions, respectively. ISS and in-flight analog environments including confinement facilities offers unique opportunities to evaluate technologies to maintain behavioral health and performances for the crew.

Performance Characteristics

The expected performances are to:

- Monitor and assess the behavioral health of the crew and to predict the potential impact on performances, including the following aspects:
    - Cognitive performance deficits, stress, fatigue, anxiety, depression, behavioral health, task performance, teamwork, and psychosocial performance must be unobtrusively monitored.
- Behavioral health indicators must enable to predict the possible impact on performances and thus may be used to support task planning.
- Prevent and counteract any observed disorders of behavioral health (countermeasures), including:
    - Selection must include team building aspects.
    - Pre-flight training must include training to prevent and solve inter-individual issues.
    - The habitable volume must be large enough and laid out to execute the necessary tasks and to provide a psychologically acceptable space for the long period of confinement.
    - Sensory stimulation (e.g., variable lighting, virtual reality) must be augmented to offset the physically and socially monotonous environment.
    - Devices must mitigate the effects of fatigue, circadian misalignment and work-overload.
    - Communication tools must offset communication delays ranging from seconds to minutes.

GER-036 – MICROGRAVITY BIOMEDICAL COUNTER-MEASURES FOR LONG DURATION SPACEFLIGHT

Description

In the years to come, deep space exploration including journeys to Mars, will be preceded by, or occur in parallel with, a return to the Moon. Unlike the Apollo era, surface stays on the Moon's surface will (eventually) become long enough that the effects of adaptation of the human body to Lunar gravity may become significant in terms of crew safety and performance. Although much is known concerning the physical and physiological adaptive responses to microgravity, virtually nothing is known about the response to Lunar (0.16 G) or Martian (0.38G) gravity and to what degree the mechanical and loading forces exerted on the body during movement in these low gravity environments might influence the musculoskeletal and cardiovascular system. Such information is vital in understanding the impact of low gravity on physiology and function, whether countermeasures will be required and whether lessons learned from microgravity can be drawn on or if new strategies are required.

Prolonged exposure to weightlessness deconditions bone, muscle, and the cardiovascular system. Other physiological systems (e.g., sensorimotor and immune) are also altered. These changes may cause decrements in both health and performance. Countermeasures must mitigate these changes with limited resources (mass, power, volume). Countermeasures may include physical (exercise), nutritional, pharmaceutical countermeasures or other integrated countermeasures such as artificial gravity. Exercise countermeasures are addressed by GER-037.

Drug safety and efficacy are highly variable between individuals. Although many people experience the desired effect, some may suffer from adverse reactions, whilst others gain little or no benefit. For this reason, in terrestrial medicine, the traditional 'one-drug-fits-all' approach is being replaced by evidence-based treatment strategies in which individual patient factors are considered. Treatment strategies for spaceflight, particularly for future exploration missions, must adopt this approach, as drug failure and/or adverse events in this environment may have particularly severe consequences.

Identification of genetic variation (e.g. in drug metabolizing enzymes) and appropriate dose correction can remove some of this variation, but other 'unknowns' related specifically to space exploration will also influence drug effectiveness, including long-term storage, space radiation and the effects of microgravity on fluid distribution and thus pharmacokinetics and pharmacodynamics. 'Modernisation' (i.e. designing out variation and side effects) of the medicines that are provided to astronauts and understanding these 'unknowns' will facilitate the production of a medical package suitable for future space exploration.

Performance Characteristics

The expected performances are:

- To prevent and counteract the physiological disorders due to the space mission environment with sizes, volumes and mass compatible with the constraints of the targeted mission.
- To monitor the physiological disorders not monitored by the medical care equipment. This includes non-exhaustively for instance:
    - Compact devices to assess and limit proprioceptive disorders, on-orbit intracranial hypertension, neurosensory disorders.
    - Optimized solutions for the use of artificial gravity.

GER-037 – MICROGRAVITY BIOMEDICAL COUNTER-MEASURES: OPTIMIZED EXERCISE EQUIPMENT

Description

Aerobic and resistance exercise is used intensively on the International Space Station and remains the best-known defence against a number of physiological changes that occur as a result of spaceflight adaptation, particularly to the cardiovascular and musculoskeletal systems. However, from an operational perspective, exercise is far from optimal, requiring a large amount of crew time, utilising oxygen and energy (from food), producing carbon-dioxide, moisture, heat, vibration) and requiring exercise hardware that must be maintained.

Exercise equipment is necessary to address muscle atrophy, cardiovascular atrophy, and bone loss associated with long-duration missions in the weightless environment of space. Current ISS exercise equipment is too large and heavy to be used on long duration missions beyond low Earth orbit. The latest equipment deployed on ISS (Combined Operational Load Bearing External Resistance Treadmill (COLBERT or T2), Cycle Ergometer with Vibration Isolation System (CEVIS), and Advanced Resistive Exercise Device (ARED)) occupies 3 International Standard Payload Racks (ISPR)s.

Performance Characteristics

The expected performances are:

- To counteract the physiological disorders by aerobic and resistive exercises with exercise equipment compatible in size and mass with the constraints of the targeted mission scenario with the maximum time efficiency.

The expectations are, for instance:

- To provide integrated aerobic and resistive exercises with a device no larger than 45 cm x 25 cm x 25 cm, with a mass of no more than 5.4 kg, requiring no external power, and accommodating a range of motion of at least 1 meter.

GER-038 – DEEP SPACE MISSION HUMAN FACTORS AND HABITABILITY

Description

Human factors technologies are required in design and operations planning to ensure adequate human performance, reduced likelihood of human errors, and increased mission safety. They must be taken into account in the design of the systems interfacing with crew (controlled, monitored or used) e.g., suit, capsule, habitat, exploration vehicle, surface lander. Technologies are required in the habitable volumes to provide a safe environment for the crew with the provision of safe air, water and an adequate food system, and to meet human environmental standards for air, water, and surface contamination (life support).

Like water and oxygen, food is essential for human survival and thus an essential resource for human space flight. Food must provide sufficient energy to keep crew in energy balance and also the right balance of macronutrients (protein, fat, carbohydrate) and quantities of micronutrients to support and maintain a range of physiological functions.

On Earth, providing an individual with the right technology and the right training (and practice) can allow them to deliver medical care at a high-standard in a number of challenging environments. However, the constraints placed on technology provision and training by human exploration missions will be unprecedented, and advanced medical systems must find ways to overcome both, allowing crew to be and remain autonomous across the widest possible range of medical scenarios.

Lastly, hibernation studies can provide added value in understanding both human factors involved in such endurance but also support the identification of habitability constraints related to providing the minimum resources to the crew.

Performance Characteristics

For human factors, the expected performances are:

- To assess human cognitive load, fatigue and health status and to predict the possible impact on performances.
- To limit cognitive load, fatigue and human errors.
- To optimize human systems interfaces accordingly.
- To provide support to adapt operation planning accordingly with in-situ capability to assist the crew with contingency mission planning and development and execution of contingency operational procedures.
- To provide expert systems to assist the crew for real time decision support including with capabilities for real-time detection and diagnosis of vehicle and habitat operational anomalies.
- To provide ground based decision support tools adapted to future mission constraints especially regarding communication delays to assist the crew with mission operational anomalies with stale telemetry. To ensure a safe environment the expected performances are to provide optimized environment control and life support capabilities. This includes non-exhaustively:
    - To recycle water, wastes and air.
    - To manage and limit wastes (e.g. optimized packing solutions).
    - To reduce food packaging volume.
    - To produce food on-board.

- To prevent, monitor and counteract microbial and chemical contaminations in the shortest time, with minimal re-supply. ECLSS details can be found in GER-029 and GER-030.

Notes / Comments

- Regarding EVA, the expected performances are to provide EVA suits answering to the specific EVA scenarios and constraints of the targeted mission.
- Reference GER-031, GER-032, GER-033 for EVA details.

GER-039 – IN-FLIGHT ENVIRONMENTAL MONITORING

Description

Extended duration missions away from low Earth orbit will require autonomous capabilities for environmental monitoring to assess the habitation environment and the recycled life support consumables and to enable the crew to anticipate, react, and mitigate any risks to continued human occupancy.

Performance Characteristics

In-flight analysis capabilities: returning samples to Earth for ground analysis will not be feasible for future beyond-LEO missions, so the capability to analyse air and water samples directly on-board is necessary to diagnose environmental habitat problems.

- On ISS, environmental habitat problems are solved by sending air and water samples to Earth for laboratory analysis (which yields data for diagnosing the problems).
- Air Monitoring is a well-developed technology but systems should be made much smaller. Some specific tests for chemicals in water and for microorganisms have been flown, but analysis needs must be specified and developed.
- Rapid detection of hazardous environmental events: The spacecraft environment must be monitored and controlled with high accuracy to promptly detect hazardous events.
- Chemical (whether predicted or not) hazards are highest in urgency, followed by microbiological threats, based on rapidity of impact.
- Detect contaminants introduced via surface activities (dust, etc.) and of importance to planetary protection.

GER-040 – FIRE PREVENTION, DETECTION & SUPPRESSION (REDUCED PRESSURE)

Description

For longer duration missions, the habitable atmosphere will likely be at a lower pressure and higher %O2 than on Space Shuttle or ISS increasing the risk of fire. Small crew cabins (e.g. Orion, ascent vehicles) preclude use of some of the current countermeasures such as Portable Breathing Apparatus. Even with larger cabins (e.g. Gateway, Surface Elements), immediate evacuation to Earth is not an available option and the crew is more dependent on replenishment of a fire protection capability than resupply. The crew is best protected by an integrated fire protection strategy.

Fire response on Shuttle and ISS:

- Shuttle Materials were screened for flammability; if flammable, storage and usage controls were enforced. If a fire alarm was activated crew would don oxygen breathing masks; cabin pressure dropped to 8 psi / 40% oxygen. If the impact of the fire or atmospheric contamination was severe, the shuttle could land quickly.
- For ISS, materials are screened for flammability; if flammable, storage and usage controls are enforced. However, experience has shown that this is difficult to maintain over long durations. If a fire alarm is activated, the crew dons oxygen breathing masks and closes the hatch(es) to affected area. If the emergency is severe, the crew will get in the Soyuz and return to Earth. GER exploration missions where the habitable atmosphere is at a lower pressure and higher %O2 has greater risk of fire than Space Transportation System (STS) or ISS; and unique challenges.

Performance Characteristics

The crew is best protected from a fire hazard by an integrated fire protection strategy including:

- Accurate definition of the risk from flammable materials in low-g.
- Identify material flammability limits in low-g ambient environment.
- Develop/validate non-flammable materials for conditions of use.
- Early fire detection from structurally integrated distributed sensors.
- Emergency breathing apparatus with filtering respirator.
- ECLS-compatible and re-chargeable fire extinguisher.
- ECLS-compatible emergency air purifier.
- Contingency air monitor for relevant chemical markers of post-fire cleanup.

Notes / Comments

Large Scale, Low Gravity Fire Demonstration: Experiments utilizing an existing automated ISS servicing vehicle (e.g., Cygnus, Dragon, ATV, HTV, Progress), or an inflatable, as a large-scale fire test platform are being planned/performed (e.g., Saffire experiments aboard Orbital ATK (OA)-6 & OA-7). Prior to re-entry, yet while a safe distance from ISS, initiate ignition of test materials while monitoring progress with smoke detectors, temperature and pressure sensors, and video recording during the event. Such experiment can validate fire detection and suppression systems, and provide realistic data on spacecraft fire to improve crew response and training.

GER-041 – SPACE RADIATION PROTECTION – GALACTIC COSMIC RAYS (GCR)

Description

Exposure to galactic cosmic rays (GCRs) is a continuous low dose exposure slightly varying due to the solar activity. Besides mainly protons, exposure comprises, heavier ions from Helium to Iron. The particle energies are so high that shielding to these particles is not very efficient. Penetration into materials results in ionization of the target atoms through nuclear interactions, and leads to target and projectile fragmentation producing secondary radiation, which prevents an effective reduction at shielding depth applicable in spacecraft design.

Lack of knowledge exists especially for the heavy ion component for the understanding of stochastic effects, like cancer, Central Nervous System (CNS) effects and hereditary effects. Heavy ions belong to the group of densely ionizing radiation. There is a difference in the radiobiological mechanisms of densely and sparsely ionizing radiation like gamma rays or fast protons. Our knowledge is mainly based on the latter group for high dose and dose rates. Therefore, there exist high uncertainties in transferring these results to low dose and dose rates and to a different radiation quality.

Heavy ions cause a unique damage to biomolecules cells and tissue, for which no human data exist so far to estimate risk. Risk models suffer from the non-availability of appropriate data sets, therefore carrying high uncertainties. These uncertainties limit our ability to accurately evaluate risks and the effectiveness of biological and physical mitigation strategies. Research indicates that mortality risk from radiation induced degenerative disease may further exacerbate the problem. In addition, there are large associated uncertainties in the modeling of the biological damage caused by GCR. Emerging paradigms in human radiation risk assessment are based on fluence – underlying physics measurement of particle type and energy spectra instead of dose.

Performance Characteristics

Technological approaches include:

- Risk quantification and uncertainty reduction through radiobiology research: Investigation of the molecular/cellular responses is needed, such as Deoxyribonucleic Acid (DNA) repair, genetic predetermination, genomic instability, epigenetic effects, adaptive response and bystander effects.
- Physical and biological dosimetry: Radiation monitoring systems are needed to assess the exposure levels of the crew, their presence is in addition required for warning from elevated exposures due to solar particle events. Benchmarking of radiation transport codes for planning purposes of future systems and missions is another main objective of the physical dosimetry. Besides scoring of chromosomic aberrations, new biomarkers could serve as advanced detection methods for a biological weighted response to different radiation qualities.
- Selection of crew to reduce risk: Selection of aged crew members will reduce the cancer risk. In addition, less radiation-sensitive humans can be selected. Individuals with identifiable genetic disposition for increased susceptibility to cancerogenesis should be excluded.
- Physical and biomedical countermeasures: Advanced shielding material has to be investigated in order to mitigate the exposure. For the chronic low dose exposure radioprotective chemicals do not serve as an appropriate tool to reduce radiation effects. Since many of these compounds occur in significant concentrations in natural food, there is an alternative offered by optimizing the dietary supply.
- Mission planning: Missions should be planned during solar maximum activity to reduce GCR exposure, the higher risks due to solar particle events can be prevented by appropriate shielding/shelter design. The development of an advanced propulsion system would remarkably reduce the risk of late effects by GCR.

Notes / Comments

- Regarding the items on risk quantification and uncertainty reduction, physical and biological dosimetry, and physical and biomedical countermeasures; access to, and use of, appropriate ground-based heavy ion accelerator facilities is required to support these approaches.

GER-042 – SPACE RADIATION PROTECTION – SOLAR PARTICLE EVENTS (SPE)

Description

Exposure to SPE particles is in contrast to the continuous low exposures through GCR, a high dose short exposure and very rare. Shielding is effective to reduce the exposure from SPEs as particles have compared to GCR moderate energies and is required mainly to prevent early Acute Radiation Syndromes (ARS). Short term dose limits for non-cancer effects has to be respected. For the most sensitive organs, the Blood Forming Organ (BFO) and the heart, this limit is set to 250 millisievert (mSv). A probability of < 10-3 not to exceed this dose limit during a mission is considered a practical limit. Of course, SPE exposures also contribute to the risk of late radiation carcinogenesis.

Protecting humans from SPE exposures is a solvable problem in the near-term through technology maturation of identified shielding solutions, through design and configuration. However, mission operational planning has a major knowledge gap of forecasting the occurrence and magnitude, as well as all clear periods, of SPEs. Management of the risk of exposure to SPEs requires an overall risk model, SPE forecasting for mission planning, SPE warnings and alerts to change mission planning, shielding options for the crew under different operational scenarios, in-mission dosimetry readings, and biological countermeasures to mitigate exposures.

Advanced Warning System: Significant risk to crew, digital equipment, and vehicle systems associated with SPEs. Assuming architectural provision for a “safe haven” or “storm shelter” within appropriate elements, successful operational implementation relies directly on the timing associated with “sounding the alarm” and crew return to these areas. Majority of exposure/SPE risk delivered early in events, making warning time/EVA or other crew “shelter” timelines critical. Advanced Radiation Dosimetry Systems Exploration missions require active crew monitoring to make appropriate changes to operations.

Performance Characteristics

- Specific technology investments are needed in the areas of:
  - Risk projection models & forecasting/probabilistic models of events and all-clear periods.
  - Heliospheric environmental monitoring technology that provides accurate alerts for SPEs.
  - Multi-functional SPE shield systems including shelters.
  - Active miniaturized dosimetry & acute biological countermeasures.
- Advanced Warning Systems: Advance warning systems exist as TRL 3-4 scientific models, available for maturation. Success of these toolsets depends on adequate provision for availability of the associated driving input data streams.
- Advanced Radiation Dosimetry Systems: Current monitoring technologies for in-mission radiation environmental measurements are either passive (crew badges, area monitors), requiring return to ground for analysis post-facto, or are larger, multi-kg, ~10W systems for ambient monitoring perhaps away from crews and sensitive vehicle systems.
- Biological Countermeasures: Countermeasures to minimize health detriment are selection of radiation resistant individuals or by increasing resistance by applying radio-protective chemicals. The latter is an appropriate method to reduce biological effects in case of high radiation exposure.
- Biological effects: In contrast to GCR exposure, the exposure by SPE is a short-term exposure mainly to protons with sometimes a small amount of heavy ions. Understanding acute effects data from therapy (whole body/partial body irradiation) has to be evaluated.

GER-045 – MARS IN-SITU RESOURCE UTILIZATION (ISRU)

Description

ISRU involves the extraction and processing of local resources, both natural and discarded, into useful products and services. In particular the production of oxygen, water, and methane that can be used for life support, propellants, fuel cell power systems, and radiation protection can significantly reduce the mass, cost, and risk of short term and sustained human exploration of Mars. The two Mars ISRU products and processes that have the biggest impact on robotic sample return and human Mars mission architectures are:

- Oxygen production from Mars atmosphere CO_2: This involves the collection and separation of carbon dioxide (CO_2) from the 6-10 torr[1] Mars atmosphere and processing the CO_2 to extract oxygen. Oxygen can make up >75% of propellant mass.
- Oxygen and fuel production from Mars soil water and atmosphere CO_2: This involves excavation of Mars soil and processing/heating above 200 C (possibly up to 600 C) to release water. Water is electrolyzed to make oxygen and hydrogen (for processing). This also involves collection and separation of carbon dioxide (CO_2) from the 6-10 torr Mars atmosphere and processing with hydrogen to make methane (or other hydrocarbon) and water. Latest findings regarding sub-surface ice from current Mars missions may influence the focus of technology development.

To date there have been no missions that have been conducted to demonstrate robotic capabilities to collect, transport and process resources in low-G environments. Technology demonstration missions are recommended to close this experience gap.

Performance Characteristics

- Atmospheric CO_2 Processing:
  - Continuous processing rates: 3.5 kg O_2/hr & 1 kg CH_4/hr 24.4 hr/sol, 300 sols
  - Power requirements: < 7 kWe/kg O_2 produced
- Water Extraction from Soil:
  - 2 kg H_2O/hr, 24 hr/day, 300 days
  - ~40 kg soil/hr excavation and processing
  - Power requirements: < 15 kWe/kg water extracted

Notes / Comments

- Note that this entry is specific to Mars as ISRU for the moon was not considered a critical technology required as per the current GER architecture. Lunar ISRU technologies which advance the TRL for Mars missions can be seen as applicable. Ongoing review of human lunar surface architecture scenarios will inform future GER revision and GER Critical Technology Portfolio updates.
- Due to the (launch) cost of interplanetary travel and especially to planetary surfaces, sustainable exploration activities can be achieved through In-Situ Resources Utilization in areas such as life support, propulsion, construction, radiation protection and waste management.

[1] unit of pressure based on absolute scale (ex: 1 torr ≈ 133.32 Pa)

GER-048 – SURFACE MOBILITY SYSTEMS

Description

Surface mobility systems allow for the movement of cargo, instruments and crew on the surface of a planetary body. Systems for transporting cargo are required to preposition cargo for future human use prior to arrival, assist in crew EVA operations and to transport payloads to launch vehicles for sample return missions. Surface mobility systems also enable scouting and exploration of possible landing sites and other areas of interest, and provide a platform for scientific instruments, allowing for data collection in multiple locations in a wide variety of locations. Low mass and low-power avionics are always in high demand for all sort of systems due to its impact on the vehicle resources (mass, volume, power).

Crew mobility systems expand crew range, speed and payload capacity while also providing power, and in the case of pressurized vehicles, habitation and environmental shelter. These vehicles need to be re-usable for multiple missions over long durations.

The current SOA for surface mobility systems are slow moving rovers with the ability to navigate low grade slopes and climb over small obstacles. Unpressurized crew mobility systems have been used for short durations on the lunar surface.

Performance Characteristics

Technology investment areas can include:

- Micro gravity climbing for exploration of features such as lava tubes.
- Roving capability to navigate soft soils on steep slopes for crater access for scientific missions and human exploration.
- Design of pressurized crew mobility systems that can be relocated remotely or autonomously for re-use on multiple missions at different landing sites.
- Improved autonomous systems for on-board decision making and planning to increase mission efficiency and reduce reliance on mission control.
- Mobile landers capable of repositioning in microgravity.

Notes / Comments

Several technologies directly related to improved surface mobility systems are discussed separately. Of significant note are GER-017 Low temperature Long life batteries, GER-019 Telerobotic Control of Robotic Systems with Time Delay, and GER-021 Autonomous Vehicle Systems Management

GER-049 – MISSION CONTROL AUTOMATION BEYOND LEO

Description

Support Missions beyond LEO in problem solving activities during remote or long-duration exploration missions, where reliance on mission control is required for task planning and/or off-nominal troubleshooting and recovery. Advanced decision-support and planning systems are needed in Mission Control to reduce operations costs and to maximize mission safety with Earth-based operators.

However, the more challenging goal of establishing a permanent human presence in space brings a scenario where ambient intelligence should not be considered only as a support to ease life and to improve productivity, as in Earth-based applications, but as a real need (or an enabling technology) to allow and protect life in critical, hazardous environments.

Performance Characteristics

- Enable Earth-based commanding and operation of vehicle or habitat at destinations with > 6-second round-trip time delay to Earth.
- Enable hand-offs in Mission Ops between ground and crew for operations in transit and at destinations with > 6-second round-trip time delay.
- Develop Tools to help Flight Controllers resolve off nominal situations after detection and initial response.
- Enable highly efficient, small staff Earth-based Mission Control that does not require 24-hr nominal support for crewed missions beyond LEO.
- Enable tools to help Flight Controllers to identify trends, get early warnings of unusual behaviours and make predictions.
- Enable intelligent tools for mixed-initiative mission planning and autonomous supervision of ground operations.
- Ambient Intelligence requires technologies to implement reliable situational awareness, to infer temporally contextualized knowledge regarding the state of the user (based on heterogeneous sensor readings and previously inferred knowledge). This appears to be the most critical gap, for the lack of technologies and competences also on terrestrial applications.*
- Advancements in the analysis of big amount of raw data to identify events and trends that may affect future state, operations, or decision making as well as the determination that a system or environment is not performing as expected (e.g. the fields of machine learning and anomaly detection).*

Notes / Comments

- ISECG/TWG performed a detailed gap assessment of Autonomous Systems with international subject matter experts (covering subject material from GER-021, GER-023, and GER-049).
- *Further information and performance characteristics can be found in the “ISECG Autonomous Systems GAP Assessment Report”.
- Per the GAT report, additional cross-cutting technology challenges applicable to Autonomous Systems were identified (see also GER-021).

GER-050 – DUST MITIGATION

Description

Technologies are required to address adverse regolith effects in order to reduce life cycle cost and risk, and increase the probability of mission success. Based on Apollo lunar surface experience, there is a risk of regolith induced system degradation. The NEO environment may include suspended “clouds” of particulates, and is in any case an unknown. Particulate mitigation will be accomplished by identification of Lunar soil contamination issues for mechanisms and thermal systems.

In addition to the particulate challenges, study results obtained by Robotic Martian missions indicate that Martian surface soil is oxidative and reactive. Exposures to the reactive Martian dust will pose an even greater concern to the crew health and the integrity of the mechanical systems. Investigate specific risk mitigation technologies; including Active Technologies (e.g. Fluidal Methods, Mechanical Methods, Electrostatic/Electrodynamic Methods), Passive Technologies (e.g. Passive Methods, Filtration Methods). Investigate Engineering and Operational Solutions including Mission Architecture Design, Hardware Design, Operational Design, and Contamination Control. In a relevant environment, integrate and test mechanical component-level technologies to TRL 6.

- Required for both robotic and human missions, NEO, Lunar Surface, Phobos/Deimos, and Mars destinations. NEO simulants are required to develop tools for anchoring, sample acquisition, etc., and Mars simulants are needed to develop ISRU technology.
- Regolith dust self-cleaning radiators needed for surface operations.
- Dust tolerant components or self-cleaning capability is needed for Lunar Surface Space Suits (Block 2).
- Active dust removal technology (SPARCLED) can also be used to acquire small-sized samples from NEOs or dust-sized samples from reduced-gravity bodies.

Performance Characteristics

Mitigation technologies must:

- maintain the solar absorptivity of a dust contaminated radiator surface within 20% of the pristine surface value, and
- provide negligible dynamic seal wear to 2 million cycles (approx. 6-month life) or 20 million cycles for a 5 year life.

Notes / Comments

ISECG/TWG performed a detailed gap assessment on dust mitigation with international subject matter experts (SMEs). Details on dust mitigation challenges, solutions, and further performance characteristics can be found in the "ISECG Dust Mitigation Gap Assessment Report" (Feb 2016). Key Findings include:

- Dust is still a principal limiting factor in returning to the lunar surface for missions of any extended duration.
- Viable technology solutions have been identified, but need maturation to be available to support missions.
- No single technology completely solves the challenges of dust, but rather a suite of technologies will be required to address them.
- Gaps in existing dust mitigation technologies have been identified and require strategies for closure before extended lunar missions are undertaken.
- Situational awareness of the dust mitigation challenges need to be infused into all aspects of mission architecture and operations.
- Investment in dust mitigation solutions increases system longevity and performance (including human-system performance).
- Resources (power, mass, volume) may be required to implement some of the mitigation solutions, but are offset by reduced logistics costs for spares, redundancies, etc.
- Solutions that work in one environment may not necessarily be fully applicable to other environments or destinations (e.g. chemistry differences, atmospheres, particles, locations on previously explored bodies).
- Trapped volatile gases are an additional factor of potential concern, which may require unique mitigation solutions.
- International cooperation within the dust mitigation community has already proved beneficial. This is currently limited to sharing information, but further opportunities are expected as commitment to narrowing the technology gap continues.

GER-051 – MARS ENTRY, DESCENT, AND LANDING (EDL) FOR HEAVY PAYLOADS

Description

Entry, descent and landing systems for Mars exploration-class missions require large surface payloads. This technology enables reliable and safe delivery of multiple 40 metric ton payloads to the surface of Mars in order to support human exploration. The benefits of focused EDL technology activities include: increased mass delivery to a planet surface (or deployment altitude), increased planet surface access (both higher elevation and latitudes), increased delivery precision to the planet's surface, increased robustness of landing system to surface hazards, and enhanced safety and probability of mission success for EDL phases of atmospheric flight.

Technology developments must begin in the next few years in order to enable an early 2040 decade pathway to human landings on Mars; multiple options must be matured for each flight regime to increase the probability of maturing a successful end-to-end system. There will need to be several flight tests in Earth's atmosphere and at Mars in order to gain sufficient confidence in these systems before relying on them for a human expedition.

Performance Characteristics

- Aeroassist, Aerocapture, and Entry
  - AAEs are defined as the intra-atmospheric technologies that decelerate a spacecraft from hyperbolic arrival through the hypersonic phase of entry. Options include deployable, inflatable, and mid-L/D vehicles, which need to be actively guided to limit loads and achieve accurate landings.
- Descent – These technology advancements primarily focus on providing greater deceleration in the supersonic and subsonic regimes in a manner that does not reduce landing accuracy or result in transient unsteadiness or loss of performance in the transonic regime. For human-class missions, inflatable and retro-propulsion technologies are options.
- Landing – The key areas of technology development are the systems to sense the surface and avoid hazards, descent propulsion motors and plume-surface interaction mitigation, touchdown systems, high-G survivable systems, and small-body guidance. Landed payloads include: Large Robotic Landers (100-1,500 kg) and Human Class (up to 45,000 kg).
- Vehicle Systems
  - EDL systems are by their nature an integrated framework of technologies that necessitate system level validation for robust maturation.
- Modeling and simulation along with atmospheric and surface characterization activities are essential for advancing these technologies.

Notes / Comments

- In-Lieu of the GER having a detailed Mars architecture, NASA Mars DRM 5.0 Mars Architecture has been used as an initial reference.
- Landing of large masses on the surface of Mars (i.e. relevantly larger than MSL) will be beyond state-of-the-art Entry, Descent and Landing capabilities. Inflatable and/or deployable decelerator and heatshield system allow to significantly extend the capabilities available today. A key element of such solutions is a robust flexible TPS technology. While important technology developments have already been done, these require further maturation and verification before entering into a Design, Development, Test & Evaluation (DDT&E) cycle.

GER-057 – LOW TEMPERATURE MECHANISMS

Description

Future deep space missions will place high demands on the mechanical system technologies, both in terms of safety and reliability over long durations and performance in extremely challenging environments, such as cryogenic temperatures and ultra-high vacuum. Long life, cryogenic actuators have been identified as a key technology challenge, and as enabling for outer planet and deep space probe missions. Long-life-by-design, modular actuators (for ease of integration) consisting of motors, gearboxes, position/speed sensors, and motor controller electronics will need to be capable of operating in dusty NEO or lunar environments, and at temperatures between +130 C and -230 C, for years, in order to meet the reliability demands.

Current state-of-the-art calls for heating to keep liquid lubricated actuators above -55 C to -70 C, with control electronics housed separately in a "warm electronics box" above -55 C. Cryo-compatible actuators / electronics would eliminate the hardware and wiring for heating (with ~30% power savings), and reduce by two orders of magnitude the interconnect cables, resulting in up to 50% reduction in mass of the electronics and electronic housings.

Performance Characteristics

- Cryogenic compatible actuator components (lubricants, bearings, gears, position sensors, motors) and control electronics which allow integration of the motor controller with the actuator, greatly enhancing efficiency at such low temperatures, reliability, modularity and scalability. These components must be operational for >10 years (2x mission life) at 10g loading (2x launch loads) within +/- 50 deg C of the local temperature.
- This technology is considered critical for lunar missions, but Architectural Conditional (i.e. IAWG in-trade space) for Mars vicinity.

GER-062 – IN-SPACE CRYOGENIC PROPELLANT STORAGE (ZERO BOIL OFF LO2; REDUCED/ZERO BOIL OFF LH2)

Description

Thermal control technologies to extend the in-space and planetary storage of cryogenic propellants require a system approach by employing passive thermal control technologies to reduce the heat input to a propellant tank through a low thermal conductivity support structure and advanced insulation, and active thermal control technologies to intercept the remaining heat with a refrigeration technique such as employing a cryocooler integrated with a Broad Area Cooling (BAC) shield attached to the propellant tank surface or embedded within the tank insulation. These technologies can significantly reduce propellant launch mass, required on-orbit margins and the complexity of vehicle operations.

LO2 Zero Boil Off (ZBO) in-space storage: uses passive thermal control technology and the integration with an active thermal control system such as a 90 Kelvin (-183 C) cryocooler with cooling tubes attached to the walls of the LO2 storage tank. LH2 Reduced Boil Off (RBO) in-space storage: uses passive thermal control technology integrated with an active thermal control system such as a 90 Kelvin cryocooler integrated with the tank support structure and a BAC shield embedded in the storage tank MLI. LH2 ZBO in-space storage: uses passive thermal control technology such as a cryocooler with two-stages of cooling.

The first stage of the cryocooler operating at 90 Kelvin and integrated with the tank support structure and a BAC shield embedded in the storage tank MLI and the second stage operating at 20 Kelvin (-253 C) and integrated with cooling tubes attached to the walls of the LH2 storage tank. These technologies are directly applicable to LO2/LH2 and LO2/CH4 propellant systems.

Performance Characteristics

- Lox Storage: Less than 8.0 Watt of active storage system power per Watt of heat removal at 90 K (-183 C); Zero boil off for > 400 days
- H2 Storage: Less than 120 Watt of active storage system power per Watt of heat removal at 20 K (-253 C); Zero boil off for > 400 days
- Cryocooler mass must be less than mass of propellant saved.

Notes / Comments

- State-of-the-art: Current in-space cryogenic propellant storage: < 24 hours. LO2 ZBO: feasibility demonstration using LN2 (simulant for LO2) with a small flight 77 K (-196 C) cryocooler developed for instrument cooling in space showed unacceptable cryocooler-to-propellant tank integration losses.
- LO2 ZBO: concept using cooling tubes attached to the LO2 test tank wall has been shown analytically to significantly reduce the cryocooler integration losses.
- LH2 RBO: BAC shield has been shown analytically to intercept a large portion of the in-space heat load to the storage tank.

GER-063 – THERMAL CONTROL

Description

All future vehicles (both crewed and uncrewed) will require thermal control systems (TCS). Improved thermal control system performance and reliability is required to reduce mass transportation requirements and enable performance over a wide range of mission requirements. Thermal control in day/night with dust mitigation on radiators is critical for continuous ops and survival. Technologies that will be required include:

- TCS fluids and variable heat rejection radiators enabling single-loop TCS architecture both in single and two-phase regime as well as Heat Switches.
- Deployable and Steerable Radiators
- Low mass/volume heat exchangers and coldplates.
- Advanced supplemental heat rejection devices including evaporative heat sinks and fusible heat sinks.
- Solid state devices (thermal electrics) and thermal sensors/health monitoring
- Operations in lunar perennially shadowed regions at cryogenic temperatures 40 K (-233 C)
- Heat storage and heat recovery systems

Performance Characteristics

- Cis-Lunar / Lunar surface: Capable of maintaining system setpoint for large turndown ratio requirements (12 kW to 1 kW); Exacerbated by low load in cold environment ~50 K (-223 C) and high load in hot environment ~350 K (77 C).
- Mars surface: Capable of maintaining system setpoint for large turndown ratio requirements (12 kW to 1 kW); Exacerbated by low load in cold environment ~0 K (-273 C) and high load in hot environment ~220 K (-53 C).
- Capable of efficient operation in rapidly changing thermal environments and/or transient heat rejection requirements.
- Reduced component and system mass

Notes / Comments

- Uncrewed surface vehicles or rover will have a much lower heat rejection compared to crewed vehicle.

GER-066 – LONG DURATION STORAGE FOR PERISHABLE GOODS

Description

For long duration missions the crew will need to store food and medication for the journey. Food stored for long durations loses nutrients over time and may spoil. Medications lose their effectiveness after a certain shelf-life. In both cases, exposure to radiation may accelerate the degradation of the stored item. Currently ISS missions are resupplied every few months so perishable items can be easily replaced as they lose their effectiveness. The stowage and tracking of the items should be automated and allow for rapid access while minimizing degradation and preventing contamination.

Human Health & Performance food-related candidate test objectives (CTO's) to enable Mars missions (ref: NASA Human Research Program (HRP) & Human System Risk Board (HSRB))

- Validate the capability to deliver a food system adequate for crew health and performance in support of progressively Earth-independent operations
- Evaluate the effects of the deep space environment on food related microbes and plans for crew health and performance
- Evaluate the effects of refrigeration and freezing on food and nutrition over long durations in the deep space environment
- Evaluate the effects of ambient stowage on food and nutrition over long durations in the deep space environment

Performance Characteristics

- Increase shelf life of critical medications to greater than 2.5 years
- Develop capability to store food such that it retains TBD% of its nutrient value after 2.5 years.
- Autonomously monitor quantity of supplies

3. CRITICAL ALTERNATIVE TECHNOLOGIES

The following technologies have been identified as being critical to mission architectures which do not currently form part of the GER baseline mission scenario but are being considered as alternatives to the baseline. Additionally, alternative technologies provide for redundancy in mission development. These entries are also considered “Architectural Conditional” & “In-Trade Space”; and are reflected by the blue dots in the destination mapping on Table 1-1 (GER Critical Technology Portfolio).

Description: Provides details on the technology, including the current state of the art or state of practice for space applications. This may include examples of international agency development efforts and/or rationale for why technology development is required, or for which mission architecture.

Performance characteristics: Objective of technology development. Details on what advancements beyond the currents state-of-the-art are required, including metrics where known/applicable. All values shown are based on available data which has been reviewed and updated by the ISECG TWG team members, however all values should be considered as generic goals which may not represent specific use cases.

GER-006 – ELECTRIC PROPULSION & POWER PROCESSING

Description

Solar electric vehicles are required for the economical transport of cargo/equipment from LEO to High Earth orbit (HEO), Cis-Lunar, and Mars Vicinity because they can significantly reduce the number of heavy lift launches required and can decrease sensitivity to mass growth of other in-space elements. The use of solar electric vehicles can also be utilized for crew transport in hybrid configurations (combined with more conventional chemical propulsion). Solar electric vehicles can increase crew safety by providing multiple redundant engines for more robust off-nominal operations.

A propulsion system requiring nominally 300 kW of electrical power is required for these missions; likely an array of 30 kW to 50 kW thrusters will be used. The current state-of-the-art is 5 kW thrusters. The highest power deep-space spacecraft using electric propulsion is Dawn, which has a maximum power to the propulsion system of 2.5 kW.

In addition to designing, building, and testing high power thrusters, technology development is required for power processing, power distribution, and propellant storage. The most common propellant used for EP is Xenon, but others such as Krypton, Argon and Iodine are possible alternatives.

Determining the performance of the integrated power and propulsion system is needed to design the subsystems, since the required performance represents such a large increase relative to the SOA. Data of interest include the interaction of the thruster plumes with the high-voltage solar array, array degradation from the Van Allen belts, and guidance, navigation and control of the Solar Electric Propulsion (SEP) vehicle with large, flexible solar arrays. Large solar arrays are needed for the SEP stage.

Performance Characteristics

- High power (~400 kW power at beginning of life)
- High specific impulse (~2,000 seconds) [TBC – still under review]
- Low mass (<~45 ton (t) wet mass with mass growth allowance to fit within a 100 t launch vehicle)

Notes / Comments

- This requires a 200x increase in thrust and 100x increase in power to the propulsion subsystem compared to the state-of-the-art.
- SEP will be used on Gateway.
- This technology is considered Architectural Conditional (i.e. IAWG in-trade space) for Mars vicinity.

GER-007 – NUCLEAR THERMAL PROPULSION (NTP) ENGINE

Description

Nuclear thermal propulsion (NTP) was identified as an option for economical transport of crew to Mars as it provides the high thrust and high specific impulse needed to significantly reduce launch mass for the heavy payloads identified. The NTP system would also reduce the cost of transits to the Moon, E-M L1, NEOs, and orbital missions to Mars and its moons.

An NTP system consists of two principal components. The first component is the primary NTP stage that includes the nuclear thermal rocket engines, RCS, avionics, auxiliary power, long duration CFM for the LH2 propellant and docking capability. The second component is an integrated saddle truss and LH2 drop tank assembly connecting the NTP stage to the mission payload that provides additional propellant storage for a wide range of mission and payload needs.

NTP has strong synergy with chemical rocket hardware and can use the same LH2 tanks in the launch vehicle. It can be developed in a timely manner at reasonable cost and can service both NEOs and Mars with same vehicle components helping to reduce overall cost.

Performance Characteristics

- High Isp (~900 s) propulsion
- Nuclear thermal rocket engines with > 100 kN of thrust
- Stable high temperature nuclear fuels, such as ceramic-metallic (cermet) fuel.
- Long duration cryogenic fluid management

Notes / Comments

NTP is currently considered Architectural Conditional (i.e. IAWG in-trade space) for Mars missions only.

GER-011 – HIGH STRENGTH/STIFFNESS DEPLOYABLE SOLAR ARRAYS FOR SURFACE EXPLORATION

Description

High power, high voltage, autonomously deployable surface solar arrays in 1/6th to 1/3rd gravity environments are needed to generate reliable electric power for surface outpost elements over the mission duration. In addition, applications for in-space use with flight elements require operations during low-g accelerations under propulsion (0.1g). Enabling features include compact stowage, reliable deployment in partial gravity, on an irregular surface and dusty environment, Martian wind load strength, Extra Vehicular Activity (EVA) compatibility, dust mitigation to limit photovoltaic power degradation and robust to surface arcing environment (Martian surface triboelectric charging).

At the present time few options exist, and only at the conceptual level. These options include mast deployed vertical, Sun-tracking blanket solar arrays for Lunar polar surface mission and horizontally deployed, fixed tent like Solar arrays. Solar array panels would employ low mass, flexible panel substrates populated with advanced photovoltaic cells, like Inverted MetaMorphic (IMM) triple junction solar cells, with bandgap tuning for the Martian surface solar spectrum substrates. These solar arrays would power outpost surface elements (e.g. habs/labs, rovers, In Situ Resource Utilisation (ISRU), lander/ascent stages, etc.) and in-flight space elements (e.g. Cryogenic Propulsion Stage (CPS), Deep Space Gateway (DSG)).

Performance Characteristics

- High power (10-100 kW), High voltage (< ~200 V)
- Autonomously deployable surface solar arrays in 1/6th to 1/3rd gravity environments
- Operability under low-g propulsion accelerations (0.1g)

Notes / Comments

This technology is considered Architectural Conditional (i.e. IAWG in-trade space) for surface missions.

GER-012 – AUTONOMOUSLY DEPLOYABLE HIGH POWER IN-SPACE ARRAYS

Description

High power, high voltage, autonomously deployable solar arrays are required to generate reliable electric power for the SEP Stage over its mission duration. Enabling features include compact stowage, reliable deployment, ~0.1g deployed strength and robust performance through the mission End-Of-Life (EOL). Leading options include large, dual-wing structures (2 x 200 kW) and modular, sub-wing structures (20 x 20 kW) employing advanced photovoltaic cells on flexible substrates.

Fine pointing requirements for concentrator-based arrays may limit functionality for some missions, so both planar and concentrator architectures should be considered. Solar array concepts that have been analytically shown to scale for use on 300 kW systems have been built and environmentally tested at the 25 kW-class size (50 kW system) and are being flight qualified at the 10 kW-class size (20 kW system).

Performance Characteristics

- High power (~400 kW at beginning of life), High voltage (~ 350 V)
- Low mass and low stowed volume (TBD W/kg and W/m3)
- Significant Cost reduction (>50% reduction)

Notes / Comments

This technology is considered Architectural Conditional (i.e. IAWG in-trade space) for Mars vicinity.

GER-013 – FISSION POWER FOR SURFACE MISSIONS

Description

Abundant power for surface missions is enabled by a surface-emplaced fission reactor. The availability of substantial amounts of continuous power provides opportunities for significant science, exploration, and engineering activities on Mars and, potentially enabling for longer duration missions on the surface of the Moon.

The GER Mission Scenario, although not specifically identifying the need for Fission Surface Power (FSP) for lunar operations, does acknowledge that human missions to the lunar surface will allow critical demonstrations of planetary exploration capabilities and techniques, while pursuing the highest priority lunar science objectives. The power-rich environment that FSP provides, enables and helps to reduce size and weight burdens on multiple systems and elements. In addition, it enhances mission operations scenarios for both Moon and Mars destinations. The GER Mars surface architecture and operations, although not defined at this time, will most likely require the use of FSP to meet the mission requirements power needs (e.g., NASA DRA 5.0 Mars architecture). The solution could be a scalable system.

Performance Characteristics

40 kWe FPS (reactor, power conversion, heat rejection, PMAD):

- 900 K reactor
- 10 kWe Stirling convertors
- 400 K radiators
- 400 V PMAD
- 150 kg/kWe for surface missions

Notes / Comments

This technology is considered Architectural Conditional (i.e. IAWG in-trade space) for Mars surface.

GER-014 – MULTI-MWE NUCLEAR POWER FOR ELECTRIC PROPULSION (NEP)

Description

Nuclear power system development suitable for very high power electric propulsion vehicles to deliver cargo and/or crew to Mars. Once built, this system's reuse capability would also reduce the cost of transits to the Moon, E-M L1, NEOs, and the Martian moons.

Primary components of NEP are:

- Reactor – heat source for the power generation, must generate power at a high temperature for a long period of time (examples of space reactor design temperatures ranging from 900 to 1500 K (or from 627 C to 1227 C).
- Power Conversion – includes both static systems (such as thermoelectric or thermionic), and dynamic systems such as Brayton, Rankine, and Stirling engines.
- Heat Rejection – waste energy from the reactor, power conversion system, electric thruster, and vehicle electronics must be rejected through radiation.
- Power Management & Distribution – Power Switching and transmission require system reliability over multiple cycles, safely switching high voltages/currents for use by the electric propulsion system.
- Electric Propulsion & Propellent – different systems may be used for continuous or pulsed acceleration methods of propulsion (e.g. Ion thrusters, Hall-Effect thrusters, Electrothermal thrusters), with each EP technology providing unique benefits and challenges. However, by decoupling the power source from the propellant, all electric propulsion systems are capable of accelerating propellant to significantly higher exhaust speeds than chemical engines (corresponding to a significant reduction in the required propellant mass).

Performance Characteristics

- High (>1 Mwe) power, low mass (<15 kg/kWe) power system for nuclear electric propulsion.
- Flight power system development and qualification.

Notes / Comments

NEP technology is considered Architectural Conditional (i.e. IAWG in-trade space) for Mars vicinity.

GER-015 – REGENERATIVE FUEL CELLS

Description

Long duration energy storage is required for extended surface missions to store solar energy and provide power during low insolation. In view of human Lunar exploration this means that missions must not end when the Sun sets for 14 (Earth) days. Therefore, alternatively to Nuclear Power Systems, technology solutions to enable the survival of lunar night have been identified for implementation in the near-to-mid-term future. Furthermore, this technology is also applicable for Mars surface applications requiring high power and/or long sortie durations.

Regenerative Fuel Cell systems (RFCS) include a fuel cell stack and an electrolyzer, each of which can be used alternately for power/water generation or for H_2/O_2 generation, respectively. There is also the option to perform in-Situ Resource Utilisation (ISRU), e.g. by using water or CO_2 being present at the destination. Electrical power can be used on any type of active space hardware. Water and O_2 can be used for life support in crewed vehicles or stations. The current technology developments include improving the stack technologies and system designs, reducing the number of ancillary components and at the same time increasing the specific energy, specific power, lifetime and reliability.

Performance Characteristics

- Power generation > 10 kWe for 8 hours or more
- Operable with reactants stored at high pressure (100 bars) to reduce tank volume, when self-pressurizing with the integral electrolyzer.
- Round trip energy conversion efficiency > 60%
- Maximize energy density to 400 Wh/kg (600 Wh/kg target in 2030)
- Operational life > 10,000 hours (40,000 hours target in 2030)

Notes / Comments

RFCS technology is considered Architectural Conditional (i.e. IAWG in-trade space) for lunar and Mars surface.

GER-047 – RAPID ACCESS EVA

Description

Provide a method of rapidly starting and ending EVAs while providing an increased level of environmental containment of potentially hazardous substances that could be encountered during the EVA

Options include (but not limited to):

- Minimal Volume Airlock – complete pressure enclosure around the EVA suit with sufficient free volume around the suits for two EVA and one IV crew to perform EVA prep/post activities.
- Suitlock – complete pressure enclosure around the EVA suit but includes a physical barrier between the pressure garment and the vehicles nominal habitable volume to minimize dust mitigation between the segments.
- Suitport – requires that the suit system to be the key portion of the vehicle pressure vessel system when attached, which creates a physical, pressure sealing barrier between the pressure garment and the vehicle's nominal habitable volume to minimize dust migration between the segments.

Performance Characteristics

- Reduce airlock operations time from 4 hours pre- and post-EVA to 30 minutes.
- Reduce exposure of habitable volume to dust, particulates, heat transport fluids, propellants, gases such as atmospheric CO2, etc.
- Reduce consumable losses from habitable volume by 660 kg over two weeks (assumes multiple EVAs/day).

Notes / Comments

GER Critical Technology Architectural Conditional (i.e. IAWG in-trade space).

GER-054 – INFLATABLE: STRUCTURES & MATERIALS FOR INFLATABLE MODULES

Description

The primary advantage of inflatable/expandable structures are the readily collapsible walls that reduce stowage volume for the launch package, but provide extra volume for living space when expanded. The resulting mass-to-volume ratio for expandable structures can be lower than that for conventional hard shell structures. The objective is to develop expandable structures technology for application as pressurized elements such as crew habitats, logistics add-ons, and airlocks. The goal is to develop expandable technology for increased deployed-habitable volume for minimal packing volume, with improved confidence in structural and thermal performance in the space environment.

Performance Characteristics

A better understanding of how inflatable structures will perform in a space environment for the long term is required, specifically in these areas:

- Long-term creep performance characterization of the structural shell of the inflatable module (material testing). We do not know how these materials (Kevlar & Vectran) perform after being under constant load for many years. This will also influence what Structural Factor of Safety to use.
- Inflatable Structure Restraint Layer damage tolerance (predictive modeling validated with testing). We do not know how to predict what type of damage the restraint layer can withstand and still be structurally sound and human-rated. This is analogous to “leak before burst” and “fracture analysis” for metallic pressure vessels. There is a potential here to significantly increase the state-of-the-art.
- Multi-layer Insulation (MLI) performance degradation prediction after folding/deployment (predictive modeling validated with testing). We do not have thermal performance of MLI after undergoing folding, launch vibration, and deployment. We must understand the MLI performance so that we can accurately predict the thermal environment of the inflatable through the various mission phases.
- Bladder material selection. The bladder is critical and very sensitive to puncture, tear, folding, handling, flex cracking, brittleness at cold, etc.
- Bladder-to-metal interface seal. This is a Crit-1 interface and has never been done on a large scale. Proper testing is important to ensure highly repeatable process.
- Predictive modeling of deployment dynamics is important to understanding the torques and loads that will be imparted to any mated module/interface during the deployment and inflation process.

Notes / Comments

- This technology is considered Architectural Conditional (i.e. IAWG in-trade space) for Mars missions.
- Need to consider lessons learned from the Bigelow Expandable Activity Module (BEAM). BEAM launched on the eighth SpaceX Commercial Resupply Service mission in April 2016 and will stay attached to the ISS until (at least) 2020. It will remain inflated for at least a four-year test period during which astronauts aboard the space station are conducting a series of tests to validate overall performance and capability of expandable habitats.
- Learning how an expandable habitat performs in the thermal environment of space and how it reacts to radiation, micrometeoroids, and orbital debris will provide information to address key concerns about living in the harsh environment of space.

GER-064 – ROBUST ABLATIVE HEAT SHIELD (BEYOND LUNAR RETURN) – THERMAL PROTECTION SYSTEM

Description

A robust, scalable heat shield TPS architecture is required that can be used for multiple missions.

While solutions exist for heat shields used on re-entry from LEO or cis-lunar orbits, the capabilities of existing ablative TPS solutions (including fully dense carbon-phenolic and carbon-carbon) will have to be confirmed for primary heat shield protection for direct return entry from beyond Lunar return conditions. New advanced and more complex ablative solutions may be considered for improved mass-efficiency. Systems that are capable of detecting critical issues with TPS or structure prior to entry improve the safety for crew.

If Mars architecture does not require direct return, then this critical technology is not required (e.g. Cis-Lunar rendezvous allows for existing Ablative TPS technology to be used (~1000 W/cm2 under ~1 atmosphere pressure).

Performance Characteristics

- Ablative TPS Solution for primary CTV heat shield capable of withstanding ~2500 W/cm2 under 0.8 atmosphere pressure. Either new ablative material, existing ablative material in new system, or new ablative material in new system will be required. Multi-layer systems or hybrid configurations will have significant mass benefit over monolithic.
- Peak heat rate dominated (~90% (TBC)) by shock layer radiation. Relevant materials (with regular productions rates) are available but performance (in particular mass) needs to be confirmed.
- Technology needs to mature sufficiently to enter Design, Development, Test & Evaluation (DDT&E) cycle including TPS development, aerothermal and shock layer radiation modeling validation, reliability/margin quantification methodology, integrated system health monitoring, hyper-velocity impact test capability and aerothermal ground test capability to approximate convective-radiative environment.

Notes / Comments

- This technology is considered Architectural Conditional (i.e. IAWG in-trade space) for Mars missions.
- In-Lieu of the GER having a detailed Mars architecture, NASA Mars DRM 5.0 Architecture used as an initial reference. DRM 5.0 has direct return entry for return to Earth.
- The GER may identify an alternate architecture design which utilizes a Distant Retrograde Orbit (DRO), which would allow the Earth return vehicle to remain in Cis-Lunar space (and subsequently only require Lunar return TPS requirements).

GER-067 – SOLID OXIDE FUEL CELL

Description

A solid oxide Regenerative Fuel Cell System (RFCs) based on Solid Oxide Cell (SOC) technology is a complex system that allows also to in-situ utilise carbon containing reactants (like CO_2 or hydrocarbons). Solid oxide RFCS may be part of a broader ISRU-based architecture in missions on the Mars surface, wherein the carbon dioxide (CO_2) present in the Martian atmosphere can be used for energy storage purpose or for providing O_2 to astronauts.

Solid oxide water electrolysis is also compatible with ISRU soil processing, where product steam can be electrolyzed and stored for fuel cell operation and/or life support. Such systems are under consideration in broader Mars architecture studies.

Current state of the art solid oxide components for space qualified RFCS are at TRL 3 to 4. These fuel cells and electrolyzers (can be one unit for both) must also operate with reactants stored at a high pressure, which requires either a reliable compressor or fuel cell and electrolyzer stacks that do not leak at elevated pressures. Large-scale energy storage capabilities would be enhanced by reliable RFCS with high specific energy, high charge-discharge efficiency, and long-life capability. In order to develop such RFCS, development efforts should focus on such objectives as high-efficiency fuel cells and electrolyzers, as well as improved water and thermal management subsystems.

Performance Characteristics

Target nominal performance characteristics notionally include:

- Fuel cells with reactants stored at high pressure (100 bars) to reduce tank volume, when fuel cells operate at independent lower pressure than supply
- Fuel cell / electrolyzer stack (one that is reversible) which operates with reactants stored at elevated pressure (10 bars) without leakage.
- Highly Reliable compressor or fuel cell with a target lifetime of ~10,000 hours of operation.
- RFCs with high specific energy (currently of 500 Wh/kg but potentially up to 1,500 Wh/kg target), and a charge-discharge efficiency of up to 70 percent.

Notes / Comments

- Added as per TWG Workshop, May 2018. (See also GER-015 – Regenerative Fuel Cells)
- Description and Performance Characteristics were taken from NASA Technology portfolio entry for solid oxide fuel cell.
- This technology is considered Architectural Conditional (i.e. IAWG in-trade space) for Mars surface.

4. ACRONYMS AND ABBREVIATIONS

AAES	Aeroassist, Aerocapture, and Entry
AR	Atmosphere Revitalization
AR&D	Automated/Autonomous Rendezvous and Docking
ARED	Advanced Resistive Exercise Device
ARS	Acute Radiation Syndrome
ATV	Automated Transfer Vehicle
AU	Astronomical Unit
BAC	Broad Area Cooling
BFO	Blood Forming Organ
BPP	Bubble Pressure Point
C	Centigrade
cermet	ceramic-metallic
CEVIS	Cycle Ergometer with Vibration Isolation System
CFM	Cryo Fluid Management
CNS	Central Nervous System
COLBERT	Combined Operational Load Bearing External Resistance Treadmill
COTS	Commercial Off-the-Shelf
CPS	Cryogenic Propulsion Stage
CTV	Crew Transport Vehicle
Dextre	Special Purpose Dexterous Manipulator
D/L	Download
DNA	Deoxyribonucleic Acid
DRM	Design Reference Mission
DSN	Deep Space Network
DTO	Detailed Test Objective
ECLS	Environmental Control and Life Support
ECLSS	Environmental Control and Life Support Systems
EDL	Entry, Descent, and Landing
EVA	Extra Vehicular Activity
FDIR	Failure Detection Isolation and Recovery
FSP	Fission Surface Power
g	gravity

G	gravity
Gbps	Gigabits per second
GCR	Galactic Cosmic Rays
GER	Global Exploration Roadmap
GNC	Guidance & Navigation Control
GPS	Global Positioning System
H	Hydrogen
HEO	High Earth Orbit
HTV	H-II Transfer Vehicle
IAWG	ISECG Architecture Working Group
IMM	inverted metamorphic
IRSIS	International Rendezvous System Interoperability Standard
ISECG	International Space Exploration Coordination Group
ISPR	International Standard Payload Racks
ISS	International Space Station
ISRU	In-Situ Resource Utilization
IV	Intravenous
IVA	Intra-Vehicular Activity
JEMRMS	Japanese Experiment Module Remote Manipulator System
K	Kelvin
kg	kilogram
kN	kilonewton
kPa	Kilopascal
kPaD	Kilopascal differential
kW	Kilowatt
LAD	Liquid Acquisition Device
LCD	Liquid Crystal Display
L/D	Lift-to-Drag ratio
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
Li	Lithium
LIDAR	Light Detection and Ranging
LO2	Liquid Oxygen
LOX	Liquid Oxygen

m	meter
Mbps	Megabits per second
mSv	millisievert
N	Newton
NASA	National Aeronautics and Space Administration
NEN	Near Earth Network
NEO	Near Earth Object, or Near Earth Orbit
NEP	Nuclear Electric Propulsion
NERVA	Nuclear Engine for Rocket Vehicle Application
NTP	Nuclear Thermal Propulsion
ORU	Orbital Replacement Unit
PAS	Power-Avionics-Software
PLSS	Portable Life Support System
PMAD	Power Management and Distribution
psia	pounds per square inch absolute
psid	pounds per square inch differential
RBO	Reduced Boil Off
RCS	Reaction Control System
RF	Radio Frequency
sec	second
SEP	Solar Electric Propulsion
SME	Subject Matter Expert
SN	Space Network
SOA	state-of-the-art
sol	solar day (Mars)
SPDM	Special Purpose Dexterous Manipulator
SPE	Solar Particle Events
STS	Space Transportation System
SWaP	size, weight and power
SWP	Solid Waste Processing
T	ton
T2 (COLBERT)	Combined Operational Load Bearing External Resistance Treadmill
TBC	To Be Confirmed
TBD	To Be Determined

TRL	Technology Readiness Level
TWG	ISECG Technology Working Group
U/L	Upload
V&V	Validation and Verification
Wh	Watt-hour
WR	Water Recovery
ZBO	Zero Boil Off


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