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ISECG MISSION SCENARIOS AND THEIR ROLE IN INFORMING NEXT STEPS FOR HUMAN EXPLORATION BEYOND LOW EARTH ORBIT

Chris Culbert
NASA Johnson Space Center, USA, christopher.j.culbert@nasa.gov

Olivier Mongrard
European Space Agency, The Netherlands, olivier.mongrard@esa.int

Naoki Satoh
Japan Aerospace Exploration Agency, Japan, satoh.naoki@jaxa.jp

Kandyce Goodliff
NASA Langley Research Center, USA, kandyce.e.goodliff@nasa.gov

Calvin Seaman
NASA Johnson Space Center, USA, calvin.h.seaman@nasa.gov

Patrick Troutman
NASA Langley Research Center, USA, patrick.a.troutman@nasa.gov

Eric Martin
Canadian Space Agency, Canada, eric.martin@acs-csa.gc.ca

The *International Space Exploration Coordination Group* (ISECG) was established in response to "*The Global Exploration Strategy (GES): The Framework for Coordination*" developed by fourteen space agencies* and released in May 2007. This GES Framework Document recognizes that preparing for human space exploration is a stepwise process, starting with basic knowledge and culminating in a sustained human presence in deep space. ISECG has developed several optional global exploration mission scenarios enabling the phased transition from human operations in Low Earth Orbit (LEO) and utilization of the International Space Station (ISS) to human missions beyond LEO leading ultimately to human missions to cis-lunar space, the Moon, Near Earth Asteroids, Mars and its environs. Mission scenarios provide the opportunity for judging various exploration approaches in a manner consistent with agreed international goals and strategies. Each ISECG notional mission scenario reflects a series of coordinated human and robotic exploration missions over a 25-year horizon. Mission scenarios are intended to provide insights into next steps for agency investments, following on the success of the ISS. They also provide a framework for advancing the definition of Design Reference Missions (DRMs) and the concepts for capabilities contained within. Each of the human missions contained in the scenarios has been characterized by a DRM which is a top level definition of mission sequence and the capabilities needed to execute that mission. While DRMs are generally destination focused, they will comprise capabilities which are reused or evolved from capabilities used at other destinations. In this way, an evolutionary approach to developing a robust set of capabilities to sustainably explore our solar system is defined. Agencies also recognize that jointly planning for our next steps, building on the accomplishments of ISS, is important to ensuring the robustness and sustainability of any human exploration plan. Developing a shared long-term vision is important, but agencies recognize this is an evolutionary process and requires consideration of many strategic factors. Strategic factors such as the implications of an emerging commercial space industry in LEO, the opportunity provided by extending ISS lifetime to at least 2020, and the importance of defining a plan which is sustainable in light of inevitable domestic policy shifts are timely for agency consideration.

* In alphabetical order: ASI (Italy), BNSC – now UKSA (United Kingdom), CNES (France), CNSA (China), CSA (Canada), CSIRO (Australia), DLR (Germany), ESA (European Space Agency), ISRO (India), JAXA (Japan), KARI (Republic of Korea), NASA (United States of America), NSAU (Ukraine), Roscosmos (Russia). "Space Agencies" refers to government organizations responsible for space activities.

I. INTRODUCTION

Space agencies participating in the International Space Exploration Coordination Group (ISECG)[1] have defined a long-range human exploration strategy that begins with the International Space Station (ISS) and expands human presence throughout the solar system, leading to human missions to explore the surface of Mars. Sending humans to Mars in a manner that is sustainable over time will be one of the most challenging and rewarding objectives of human space exploration in the foreseeable future. These missions will require new technologies and significant advances in the capabilities, systems, and infrastructure. Transforming this strategy into a roadmap involves identification of feasible pathways and the definition of mission scenarios that build upon the capabilities of today, drive technology development and enable scientific return.

As part of the Global Exploration Roadmap[2], ISECG has developed several optional global exploration mission scenarios enabling the phased transition from human operations in Low Earth Orbit (LEO) and utilization of the ISS to human missions beyond LEO leading ultimately to human missions to cis-lunar space, the Moon, Near Earth Asteroids (NEAs), and the Mars system. Of these, two mission scenarios are considered likely pathways for human missions after ISS: 1) Asteroid Next and 2) Moon Next. They differ primarily with regard to the sequence of sending humans to the Moon and asteroids and each reflects a step-wise development and demonstration of the capabilities ultimately required for human exploration of Mars. For each scenario, a conceptual architecture was considered that included design reference missions and notional element capabilities. Design reference missions are generally destination focused, yet they comprise capabilities that are reused or evolved from capabilities used at other destinations.

This paper describes the Guidance, Goals, and Objectives guiding the mission scenarios in Section 2. Section 3 discusses the destinations and the various challenges associated with those destinations. The mission scenarios are presented in Section 4. Section 5 reviews the design reference missions and Section 6 discusses the major capabilities included in the mission scenarios.

II. GUIDANCE, GOALS AND OBJECTIVES

Agencies participating in the development of the mission scenarios have agreed on strategic guidance[2] to inform the development of the ISECG mission scenarios. The purpose of the strategic guidance is twofold:

- To guide the development of the different ISECG mission scenarios;
- To support the assessment of ISECG mission scenarios that will inform agencies in identifying their next steps.

The strategic guidance reflects the intent of participating agencies for defining sustainable, affordable and robust exploration scenarios taking due account of ISS lessons learned. The following common guiding principles have been defined:

1. Capability driven framework: follow a phased/step-wise approach;
2. Exploration value: generate public benefits and meet exploration objectives;
3. International partnerships: provide early and sustained opportunities for diverse partners;
4. Robustness: provide for resilience to technical challenges;
5. Affordability: take into account budget constraints;
6. Human and Robotic partnership: Maximize synergy between robotic and human missions.

In addition to the strategic guidance, agencies agreed on exploration destinations and have developed a set of destination specific common goals[3]. These destinations of interest are the ISS, LEO, cis-lunar space, Moon, NEAs, and Mars System. Further information can be found in Section 3. The common goals define specific interest for visiting these destinations with robots and humans. Destination specific common goals are not intrinsically time bound and the full achievement of some of these goals may take many decades. Common goals together with benefits resulting from exploration activities provide the overall rationale for humans to explore. Table 1 presents an overview of the Goals and Objectives.

Goal	Definition
Search for life	Determine if life is or was present outside of Earth and focus on understanding the systems that support or supported it.
Extend Human Presence	Extend human presence beyond low-Earth orbit with a focus on continually increasing the number of individuals that can be supported at these destinations, the duration of time that individuals can remain at these destinations, and the level of self-sufficiency.
Develop Exploration Technologies and Capabilities	Develop the knowledge, capabilities, and infrastructure required to live and work at destinations beyond low Earth orbit through development and testing of reliable and maintainable technologies, systems and operations in an off-Earth environment.
Perform Science to Support Human Exploration	Reduce the risks and increase the productivity of future missions in our solar system by characterizing and mitigating the effect of the space environment on human health.
Stimulate Economic Expansion	Support or encourage provision of technology, systems, hardware, and services from commercial entities and create new markets based on space activities that will return economic, technological, and quality-of-life benefits to all humankind.
Perform Space, Earth, and Applied Science	Engage in science investigations of and from solar system destinations and engage in applied research in the unique environment at solar system destinations.
Engage the Public in Exploration	Provide opportunities for the public to engage interactivity in human space exploration.
Enhance Earth Safety	Enhance the safety of planet Earth by following collaborative pursuit of planetary defence and orbital debris mitigation mechanisms.

Table 1: Goals and Objectives

III. DESTINATIONS

The destinations of interest in the ISECG mission scenarios are ISS, LEO, cis-lunar space, the Moon, NEAs, and the Mars System. The requirements for getting humans to ISS and LEO are well understood as ISECG nations have been placing humans and assets in these locations for many years. However, long-duration interplanetary space missions and landing on other planetary bodies and moons present unique challenges for the crew, spacecraft systems, and the mission control team. The cumulative experience and knowledgebase for human space missions beyond six months and an understanding of the risks to humans and human-rated vehicle systems outside of the Earth's protective magnetosphere requires further investigation. A variety of challenges exist, including radiation exposure (cumulative dosage and episodic risks), physiological effects, psychological and social-psychological concerns, habitability issues, system redundancy, life support systems reliability, missions contingencies, abort scenarios, consumables and trash management, and communications light-speed delays. Figure 1 depicts the relative durations and total mission energy (total mission velocity increment starting from a LEO orbit) of some typical Design Reference Missions studied by the participating agencies.

International Space Station

The International Space Station (ISS) is a working laboratory orbiting 380 km above the Earth travelling at 28,000 km per hour and is home to an international crew of 6. It is the most complex scientific and technological endeavour ever undertaken, involving support from five space agencies representing 16 nations. As a research outpost, the station is a test bed for future technologies and a research laboratory for new, advanced industrial materials, communications technology, medical research, and much more.

The ISS plays a key role in advancing the capabilities, technologies, and research needed for exploration beyond LEO. Research and technology development in critical areas such as habitation systems and human health research will enable risk reduction for long duration missions. Demonstration of exploration technologies, including advanced robotics and communication technologies will inform exploration systems and infrastructure definition.

Low Earth Orbit

Low Earth Orbit (LEO) is generally defined as the region of space from the Earth's surface up to 2000 km altitude. LEO is the closest destination to Earth's surface and therefore the least delta velocity intensive. All missions beyond LEO must at least transit through this region. Human tended stations to date, such as Mir, Skylab, and ISS, have been located in LEO as it is the logical initial step in developing long duration in-space experience due to the relative ease of access, abort capabilities and lower propellant requirements. In case of contingency or emergency in LEO, the crew can be brought back to Earth typically within a couple hours.

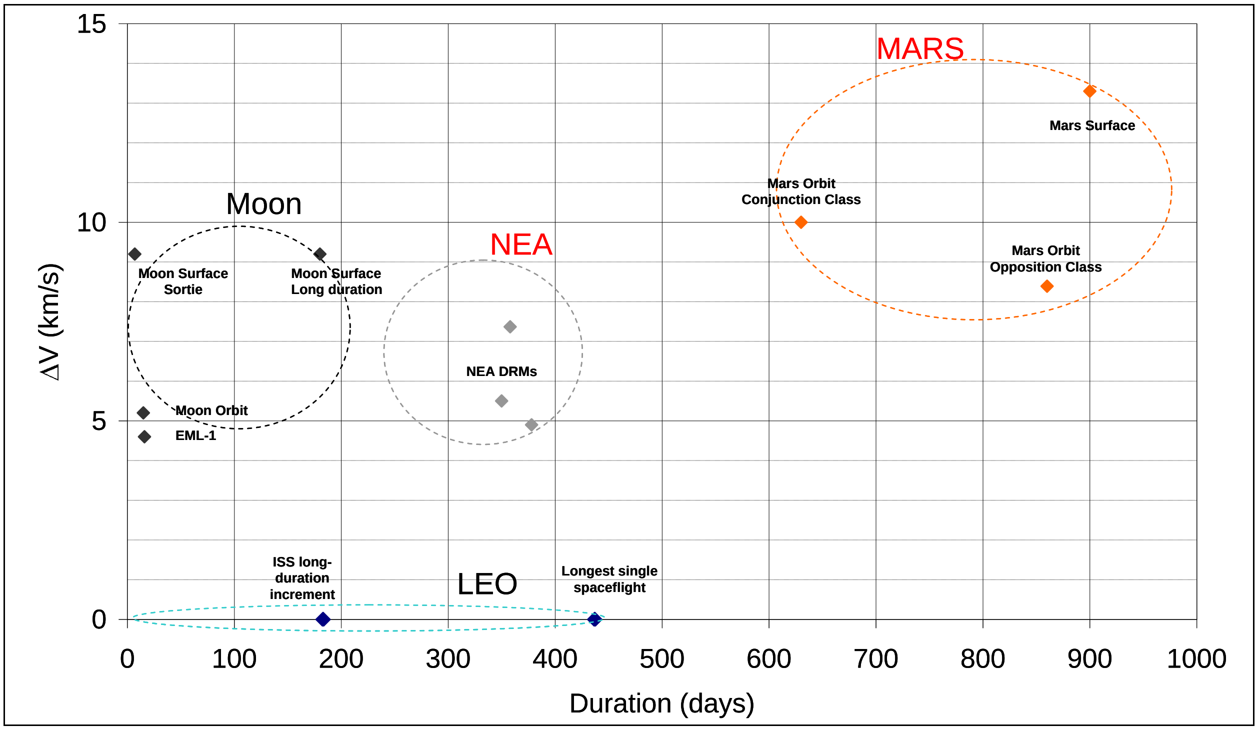


Figure 1: Complexity in term of duration and velocity increment from LEO across destination of interest.

The radiation environment in LEO is more favourable than other identified destinations due to the Earth's magnetosphere, which has a protective function against solar and cosmic radiations. A particular issue in LEO is posed by space debris from human activities. Currently in LEO more than 8,500 objects larger than 10 cm are being tracked along with many smaller objects which cannot be tracked from ground due to their size.

Cis-lunar

Cis-lunar space is defined in the context of the ISECG scenarios as all Earth orbits beyond LEO including High Earth Orbit (HEO), Geosynchronous Earth Orbit (GEO), the Earth-Moon Lagrange points, and lunar orbits above ~100 km. In general, access to cis-lunar space requires significantly more energy to overcome Earth's gravity and return the crew when compared to LEO. To access destinations in the vicinity of the Moon (e.g., Earth-Moon Lagrange Point 1 (E-M L1) and lunar orbits) and return crew, delta velocity requirements are approximately 5 km/s more than LEO. GEO is the most challenging location, with delta velocity requirements approximately 6 km/s more than LEO.

The radiation environment in cis-lunar space beyond Earth's magnetosphere is a more challenging environment to protect crew health, in particular, against Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPE). The specific radiation environment in some intermediate orbits above LEO, but still within Earth magnetosphere can also be challenging due to the presence of high energy electrons and protons trapped along the Earth magnetic field lines called the Van-Allen Belts.

In case of contingency or emergency abort situations, cis-lunar destinations generally require longer return durations when compared to LEO. For GEO missions, the crew return generally takes up to a day. For E-M L1 missions, the crew return can take 3-4 days. For lunar missions, returning the crew to Earth nominally takes from 3-5 days and up to 14 additional days depending on current location in the orbit, orbital phasing, and the additional propellant carried to perform orbital manoeuvres.

Moon

Low lunar orbits (up to ~100 km) and the lunar surface are considered part of the "Moon" destination. For the ISECG mission scenarios, crewed stays on the lunar surface are limited to a polar location (North or South Pole) due to power requirements and delta velocity constraints. The delta velocity constraints are driven by the ability of the crew capsule/service module to perform a plane change that supports a range of contingency surface abort scenarios. The power requirements are less challenging at the polar regions driven by the shorter eclipse durations and longer periods of sunlight. For the ISECG mission scenarios, one of the lunar poles is assumed due to the favourable solar and thermal conditions, thus not exposing the systems to the harshest operational environment of a full approximately 15 day lunar night that can be encountered elsewhere on the lunar surface.

The lunar surface temperature is a function of the solar incidence. During noontime, it is around 100°C, whereas the coldest night temperature is around -150°C. The polar areas, which are foreseen landing sites in ISECG mission scenarios, are always either dark or at grazing solar incidence. The average temperatures in the lit areas are approximately -50°±10°C. Their solar conditions permit continuous power and are a benign thermal gradient environment. The dark areas are very cold, with estimated values between -225°C and -200°C.

The lunar environment requires a strategic approach to management of lunar dust and regolith. This environment has an impact on many systems such as lunar rovers or extra-vehicular activity (EVA) suits (abrasion and wear, seals, etc.) as well as on crew-related aspects such as crew efficiency (maintenance and cleaning) and human exposure (inhalation and irritation). It also has an effect on electrical systems due to lunar dust specific charging processes. The radiation environment is similar to a cis-lunar space environment.

Communication from the lunar surface to Earth is straightforward from the near-side since there is continuous visibility to Earth. However, on the far-side there is no direct to Earth communication opportunity. At the poles, due to the libration movement of the Moon, there is a loss of direct communication opportunity to Earth for about 12 consecutive days per lunar month.

As for the cis-lunar destinations, in case of contingency or emergency in lunar missions, returning the crew to Earth nominally takes from 3-5 days up to 14 days depending on the additional propellant carried to perform additional orbital manoeuvres.

Near-Earth Asteroids

Near-Earth Asteroids (NEAs) provide an intermediate destination for human missions between the Moon and Mars that, among other benefits, can reduce the risks for all deep space exploration. NEA missions can provide important scientific discoveries and vital operational experience for Mars missions and beyond, assist in the development of planetary defence approaches, and foster the future utilization of space resources.

It can be seen in Figure 1 that the total mission energy for some NEA trajectories can be less energetic than for lunar surface missions, while other trajectories (not shown in Figure 1) can exceed that needed for Mars missions. Durations are significantly longer than travelling to and from the Moon. Longer NEA mission durations of a year or more are commensurate with the in-space transit segments for sending humans to Mars. NEAs are challenging targets as their minimum energy opportunities typically occur less often than Mars missions since many have long synoptic periods. However, asteroids in Earth-like orbits can have continuous departure windows that can last many months and repeat for several years. Since there are many more smaller NEAs than larger ones, mission opportunities are constrained by the minimal NEA size deemed acceptable for a future human mission.

Since NEAs have very low surface gravity, the mission will not require a surface lander in the traditional sense. A significant challenge will be to station-keep alongside the NEA or “dock” and anchor to the NEA’s surface. Asteroid spin rate and surface/internal structure are significant factors that influence this operational challenge and are significant factors in target qualification. Small asteroids (~50-100 m or smaller) have a tendency to be fast rotators and are more likely to be monolithic with less surface regolith. Large asteroids (~100 m or larger) tend to rotate more slowly and have a high probability of being rubble piles comprised of a variety of particle sizes. Anchoring to a rubble pile in a microgravity environment represents a critical challenge for NEAs and potentially for the future exploration of the Martian moons Phobos and Deimos.

NEAs are objects in orbit around the Sun and thus a spacecraft visiting such object must leave the Earth-Moon system. In case of contingency or emergency during NEA missions, it is not possible in most cases to perform an abort back to Earth and the full duration of the mission shall still be committed. Hence several months or close to one year could be spent in space before a return opportunity exists in case of emergency.

Mars System

Mars orbits, Mars’ moons Phobos and Deimos, and Mars surface are the domain of the Mars System. These destinations are the most difficult of the current ISECG destinations set and are often referred to as the ultimate destination or goal of current exploration efforts. Transit to and from the Mars System is generally binned into short stay or “Conjunction” class and long stay or “Opposition” class missions. Missions to the Mars System have regular quantified departure opportunities unlike NEAs.

Missions to Mars orbit and its moons are energetically comparable to the more difficult NEAs (a delta velocity range of 8.5–10 km/s) and represent scientifically interesting destinations. As can be seen on Figure 1, total durations for these missions are 2 to 3 times longer than proposed NEA missions and will require several years without possibility of abort back to

Earth. Proximity operations near Phobos and Deimos pose challenges similar to those encountered exploring very large NEAs. However cargo can be robotically pre-positioned for use when the crew arrive in the Mars System in a manner similar to Lunar and cis-lunar destinations.

The surface of Mars is an even more difficult destination energetically, logistically, and from an energy generation perspective. The crew and all the equipment needed for their mission and return to orbit must descend into Mars' gravity well and safely land. Mars' diameter is roughly half the Earth's and twice the Moon's; it is intermediate in size, mass, and surface gravity. This makes it more difficult than landing on the Moon, but easier than landing on Earth if a powered landing is used. Earth's thicker atmosphere allows it to be used effectively to decelerate entering payloads as compared to Mars thinner atmosphere. Any pre-positioned assets on the surface must be nearby the crew landing location and functional for the mission to be a success. Mars has temperatures ranging from -5°C to -87°C with a mean of -63°C. The atmosphere is less than 1 percent of Earth's surface pressure made up primarily of carbon dioxide, nitrogen and argon with traces of oxygen and water. Atmospheric (and regolith) In-Situ Resource Utilization (ISRU) can provide significant resources for propellant and life support, however these systems must operate reliably for some duration prior to crew arrival for mission success. Mars typically has dust storms when it is closest to the Sun that can cover the entire planet; these can complicate entry descent and landing as well as significantly reduce surface solar power systems output. Mars dust presents human health and mechanical issues and concerns similar in nature to lunar regolith, however its chemical makeup is vastly different and mitigation may not be identical.

IV. MISSION SCENARIOS

Five notional mission scenarios for Human space exploration were developed to reflect the "capability-driven/objectives based" framework embraced by the ISECG. Such an approach is considered most effective to enable a sustainable human exploration program. The primary objective of the scenario development is to provide insights into what could be capability investments for ISS and following ISS in the context of a sustainable and affordable exploration campaign. Each of the scenario options explores possible next steps which are considered reasonable and achievable based on current global capabilities and technology development plans. These scenarios are:

1. Scenario 1A – Implement the ISECG Reference Architecture for Human Lunar Exploration[4] with updated transportation architecture assumptions. (Not Pursued)
2. Scenario 2A – Implement an early NEA mission, developing the capabilities to do NEA missions as soon as possible. (Not Pursued)
3. Scenario 2B – Implement a 'deep space habitat' as the next step. Perform risk reduction activities and use the 'deep space habitat' for a number of objectives in cis-lunar space before going on a NEA mission.
4. Scenario 3A – Implement a lunar cargo descent stage/8 t Lander early, followed by an ascent stage 3-4 years later, with tele-operation of lunar robots from Earth and lunar orbit in support of crewed activities. The lunar surface exploration objectives are expected to be limited to those required to prepare for Mars and conduct best science informed by the robotic ops.
5. Scenario 3B – Implement a 'deep space habitat' prototype as the next step and use it in cis-lunar space in coordination with lunar robots and as a potential human lunar mission staging point. (Not Pursued)

Scenarios 1A, 2A, and 3B were assessed and judged to be not sufficiently responsive to the goals, objectives and strategic guidance agreed on by participating agencies. Another pathway that would set humans on the surface of Mars as the "next step" was also considered based on work done within ISECG participating agencies and was not considered feasible because of risk, cost, and technology readiness concerns. Figure 2 shows the optional pathways for the two remaining mission scenarios, Scenario 2B (named To Mars with Asteroids as the Next Step) and Scenario 3A (named To Mars with the Moon as the Next Step).

Mission Scenario Assumptions

Assumptions were used to establish the mission scenario philosophy in accordance with stakeholder guidance. An assumption is a basic or governing principle used as a point of departure for trades during the course of the study. The assumptions were established based on guidance from the:

- Exploration Roadmap Working Group,
- International Architectures Working Group,
- International Objectives Working Group,
- Internal and external constraints, design practices, and existing requirements.

A subset of the overarching assumptions is listed in Table 2 and applies to both mission scenarios.

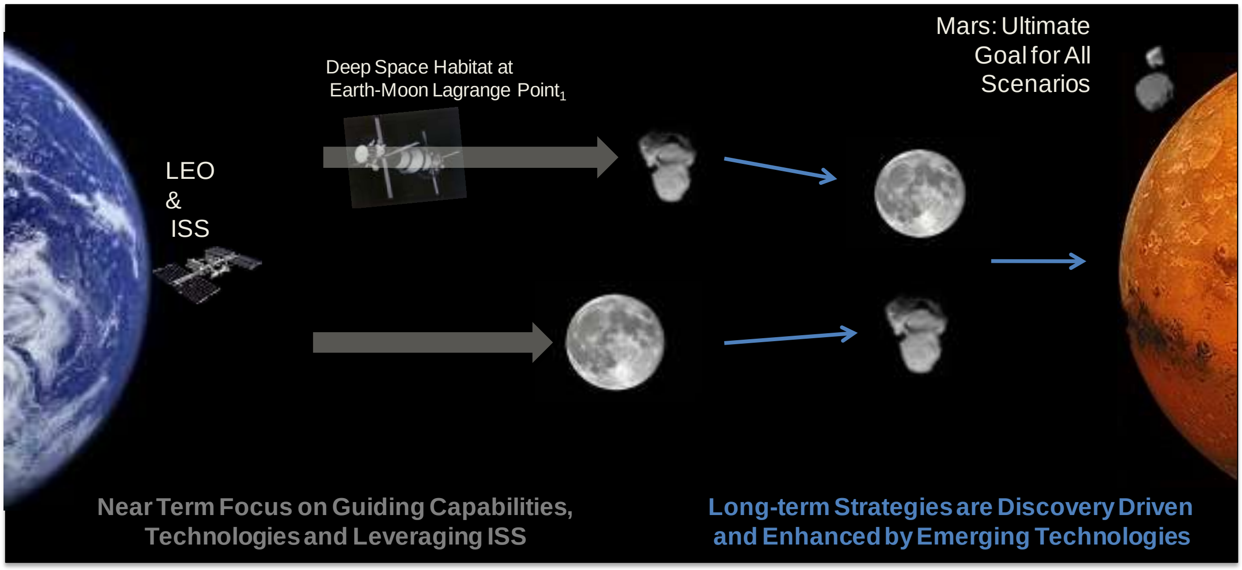


Figure 2: Optional Pathways in a Common Strategy

Assumptions	Rationale
ISS will end operations around 2020	Based on the current international plan
An eventual goal of this architecture is the future human exploration of Mars	ISECG agreement
All dates in the mission scenarios are emphatically notional, assumptions for flight rate across transportation systems will inform actual achievable dates	Pre-phase A conceptual study
There are two dissimilar redundant capabilities for crew transportation to LEO and cis-Lunar space	Potential for more than one crewed mission per year beyond LEO with utilization of all international transportation capabilities
There shall be a minimum of one crewed mission per year starting in the year of crewed destination exploration	Establishes a minimum number of crewed missions per year as a combined National Agencies crew delivery capability to maintain sustainable exploration

Table 2: Overarching Assumptions for the Mission Scenarios

To Mars with Asteroids as the Next Step

To Mars with Asteroids as the Next Step, Asteroid Next for short (Figure 3), focuses on advancing the capabilities necessary to travel and live in deep space, building on the significant work done on the ISS. An opportunity has been identified that could leverage assets previously emplaced on ISS to act as initial capability test beds for emulating future exploration system capabilities. This extension of ISS associated assets would then be followed by the deployment of a new "deep space habitat", allowing the advancement of habitation systems to be demonstrated in a deep space environment. In parallel, advanced propulsion technologies and capabilities would be matured through ground based technology development efforts, in-space testing of prototypes on ISS or its vicinity and eventually robotic precursor technology demonstration missions. When the reliability and sustainability of the habitat is demonstrated, deep space exploration missions would begin. At least two NEA missions are envisioned within the 25-year timeframe. This scenario offers the fastest path to a Mars orbital mission with opportunities to explore Phobos and Deimos and tele-operate highly capable Mars surface rovers. A follow-on Mars surface mission would either have to accept greater levels of surface system operations risk or the scenario could later include system testing on the lunar surface before a crewed Mars surface mission was performed.

ISS Utilization & Demonstration

ISS already plays a significant role in development and testing of future exploration technologies and capabilities. However, more radical steps in testing future exploration systems at the component and system level with incrementally less reliance on the ISS resources are prudent to fully utilize ISS potential and better prepare for deep space exploration. This could be

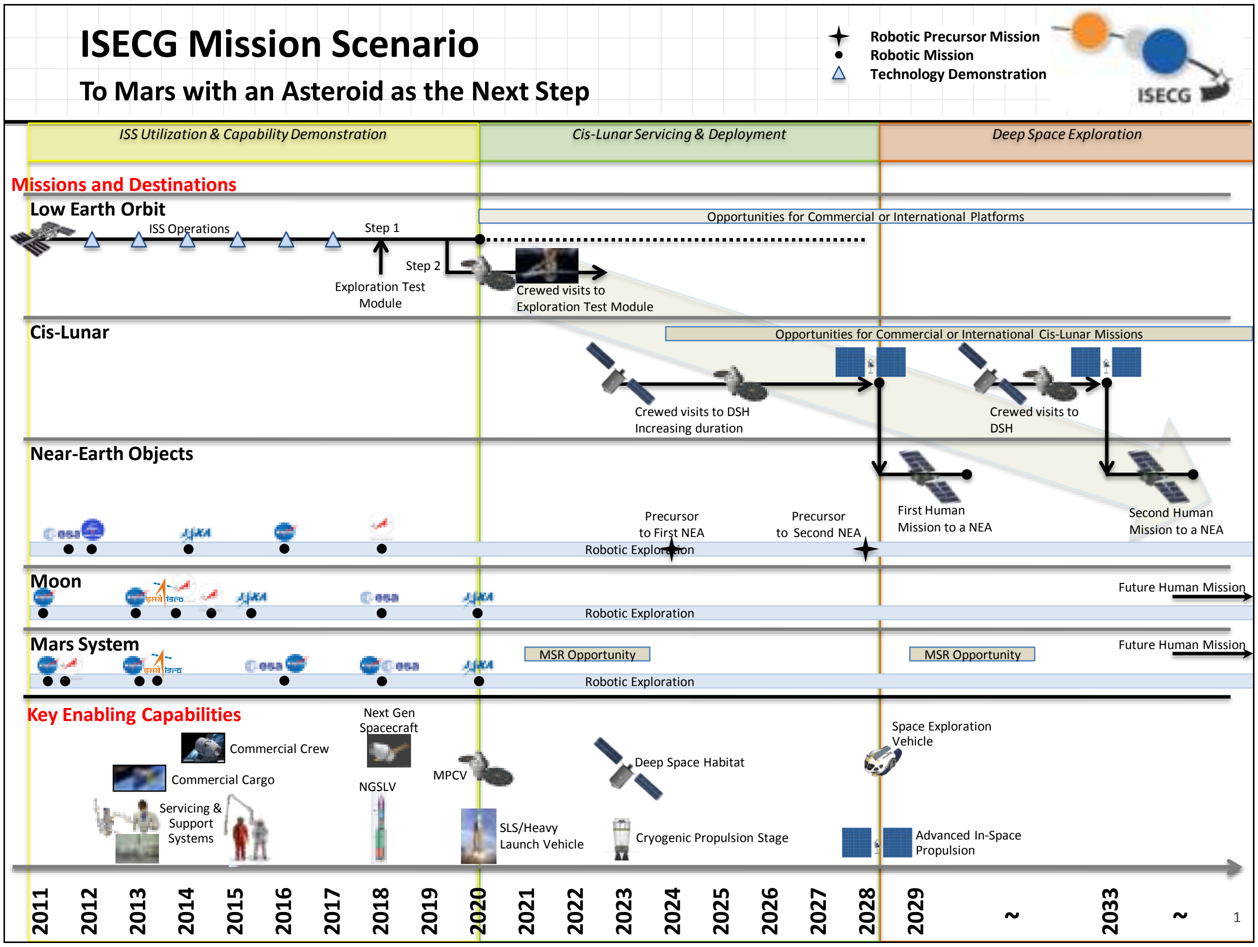


Figure 3: To Mars with Asteroids as the Next Step Mission Scenario

accomplished by adding one or more modules to the ISS later in life that would test a set of proto-flight exploration systems in an integrated manner. These systems could include environmental control systems (higher reliability, lower mass, additional closure), low power, radiation hardened avionics and next generation EVA suit port systems, all operating at reduced pressures (ISS currently at 14.7 psi, exploration systems would likely be operated at below 10.3 psi) and with additional on-board autonomy. Additional external modules/systems could be added to ISS to test long-term cryogenic fluid management, high bandwidth communications, advanced power and new propulsion systems. These dedicated capability demonstration modules offer partnership opportunities that leverage our ISS investment while offering a direct link to developing the capabilities required for exploration beyond LEO. These ISS tested modules and systems, if configured appropriately, could then be assembled into a co-orbiting facility that would break the bond with ISS as the next step towards validating beyond LEO exploration capabilities. If ISS were not to be extended at this point, the co-orbiting facility could be used as a destination for testing new crew transportation systems and as an anchor for new commercial and international opportunities in LEO.

Cis-Lunar

The next step beyond LEO is enabled by the progressive testing and validation of advanced exploration systems in the ISS vicinity, better understanding of human health and performance in a long term microgravity environment and the availability of increasingly capable transportation infrastructure for launch, in-space and beyond LEO crew transportation. Cis-lunar space is the next destination beyond LEO that becomes a proving-ground for systems intended to enable deep space exploration.

Crewed missions beyond LEO assume at a minimum spacecraft systems with weeks of life support, capability for four crewmembers, and the ability to return them or accommodate abort from cis-lunar space while being able to handle the entry heat load associated with cis-lunar entry velocities. In order to get such a vehicle to its cis-lunar destination from LEO, a large in-space chemical stage is required. These systems (and their propellant) can be launched to and assembled in LEO by multiple smaller launches or in a single launch via a Heavy Lift Launch Vehicle (HLLV). The current scenarios assume two crewed transportation systems have been developed to support beyond LEO exploration, and that at least one of them includes a HLLV capable of lifting 100 t to LEO.

The Asteroid Next scenario uses cis-lunar space as the next logical step towards enabling NEA and Mars orbital missions. A long-term Deep Space Habitat (DSH) is deployed to either E-M L1 or a HEO orbit (that would minimize duration and exposure within Van Allen Radiation Belts) that will be used as an eventual staging point for a NEA mission. The DSH is eventually configured and used as the habitat for the first NEA mission but begins as a capability demonstrator for increasingly longer crewed stays. This approach yields a progressive understanding of the impacts of deep space operations on habitat systems and the crew, as well as offering opportunities to “practice” elements of the first NEA mission. This period also offers opportunities for application of human exploration capabilities to non-exploration missions such as the deployment and servicing of space assets and science related to microgravity (Figure 4), as the DSH has a potential to offer a better microgravity environment than ISS (in the absence of crew movement/exercise). These cis-lunar missions could be based from the DSH or flown as separate missions to test and refine exploration systems, such as a Cryogenic Propulsion Stage (CPS), Space Exploration Vehicle (SEV), Multi-Purpose Crew Vehicle (MPCV), etc., that will provide proximity operations, rapid EVA, and robotic manipulator capabilities at NEAs and the moons of Mars. These missions could include rescue of an older satellite to prevent it from contributing to the orbital debris problem, deployment and servicing of space telescopes, and even deployment, inspection and repair of the exploration systems themselves.

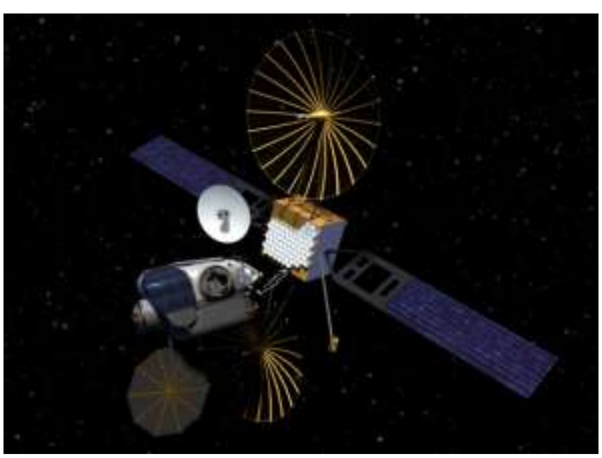


Figure 4 – Notional Cis-lunar Servicing Mission

The Asteroid Next scenario also leverages the development of advanced in-space propulsion to increase the available set of NEA targets that can be reached, to decrease launch needs while increasing the capabilities for exploration available at the destination and to build a quicker path towards Mars. During the cis-lunar phase, progressively scaled testing of these advanced propulsion capabilities will be required which also may create crewed mission opportunities. These scaled advanced propulsion demonstrations could be combined with delivery of logistics and upgrades to the DSH, culminating with full scale demonstrations that at the end of the cis-lunar phase, have prepared humanity to begin exploring deep space.

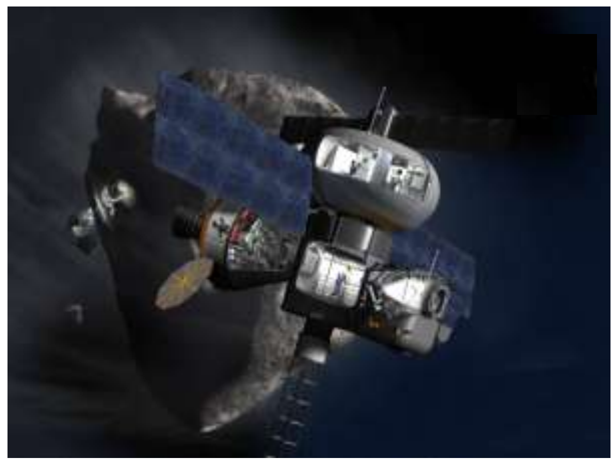


Figure 5 – Notional NEA Exploration Mission

<u>Deep Space Exploration</u>

Sending humans to NEAs (Figure 5) will be the first time humankind will venture beyond the influence of the Earth’s magnetosphere, exposing the crew nearly to the same radiation environment as that of a Mars mission. NEAs are high value science targets in their own right but understanding them better will also refine Earth impact mitigation strategies. NEAs are challenging targets as their minimum energy opportunities occur less often than lunar and Mars missions and may not repeat on a regular basis. Some are solid, some are an aggregation of dust, and all rotate at various rates. Precursor robotic missions to the eventual human mission targets will allow for refinement of destination systems performance that will be required to explore the chosen NEA. The current scenarios assume a range of capabilities from stand-off EVA to attaching a small exploration vehicle to the NEA to serve as a base for exploration. There are also not many known large targets that can be travelled to in a year’s or less time without an excessive number of launches. The Asteroid Next scenario includes the application of advanced propulsion such as solar electric propulsion (SEP) or nuclear thermal propulsion (NTP) enabling a larger set of potential NEA targets.

During the first NEA mission and prior to and during a second NEA missions, there are still opportunities to perform cis-lunar servicing and deployment missions, as well as lunar orbital missions. These missions have not yet specifically been called out in the Asteroid Next Mission Scenario Chart, (Figure 3). The Asteroid Next scenario features a second NEA mission, most likely to a more challenging target. Options at this point include more NEA missions, a Mars orbital mission or a return to the Moon to exercise surface systems before attempting a crewed mission to the surface of Mars.

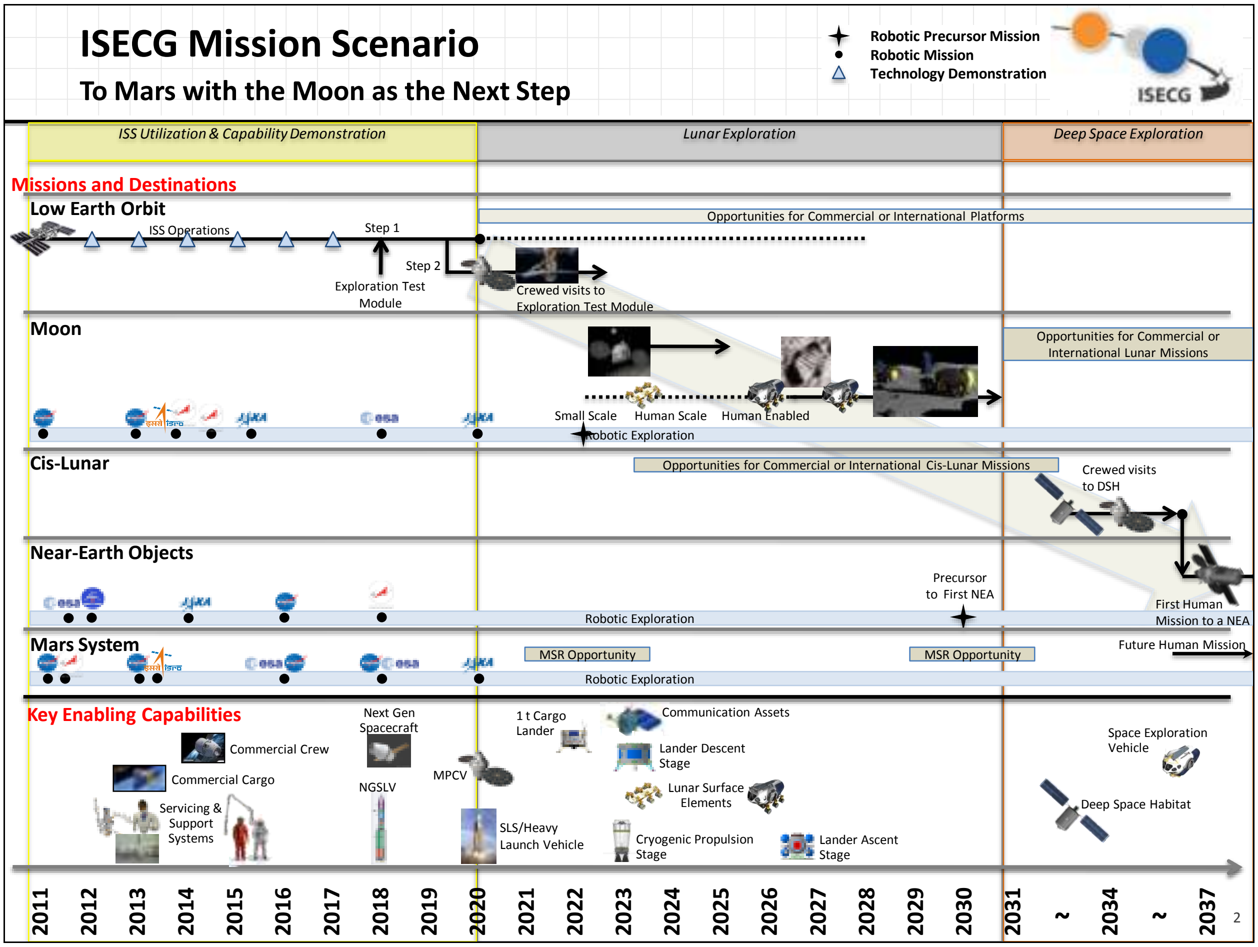


Figure 6: To Mars with the Moon as the Next Step Mission Scenario

<u>To Mars with the Moon as the Next Step</u>

To Mars with the Moon as the Next Step, Moon Next for short (Figure 6), has an early focus on advancing the capabilities needed for planetary surface exploration. It drives the readiness of technologies needed for surface exploration of Mars, such as extreme surface mobility in partial gravity, operation in a dusty environment, and surface power. The scenario builds on the information gathered from numerous robotic missions to the Moon to enable in-situ human explorers to maximize their time on the surface to advance scientific knowledge and refine surface operations techniques. This scenario is focused on achieving Mars surface exploration risk reduction activities, recognizing that there are other objectives that would require longer stays on the Moon to be achieved. Findings regarding lunar resources or other discoveries may drive the interest in longer stays on the Moon, perhaps ultimately the construction of a lunar base on the Moon, but this is not included in this scenario. Later in the scenario, investments in deep space exploration capabilities are included to enable a mission to a NEA.

<u>ISS Utilization & Demonstration</u>

The Moon Next scenario has a very similar ISS utilization and demonstration phase when compared to the Asteroid Next scenario. The priority for long duration habitation systems is not as high initially in the Moon Next scenario because of its early focus on surface exploration, so these investments can be spread out longer across this phase and also run concurrent with the lunar exploration phase. The Moon Next scenario introduces a novel development philosophy during this phase that features development and application of the uncrewed aspects of the human scale lunar lander and surface mobility systems first, followed by development of the crewed portions of those systems later (ascent module and pressurized rover cab). This approach may phase development costs better while affording multiple partnership opportunities and allowing rigorous testing of lander and mobility chassis before the crew has to rely upon them.

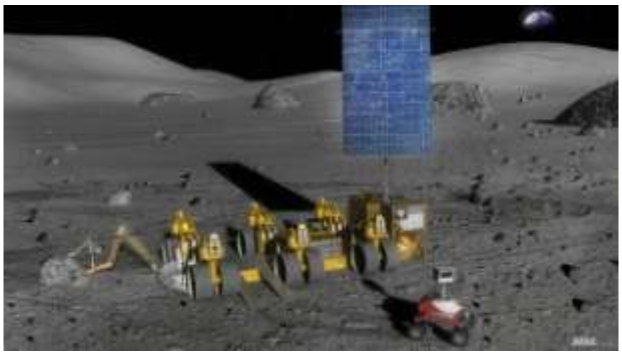


Figure 7 – Notional Lunar Surface Exploration

Lunar Exploration

The lunar exploration phase comes next for the Moon Next scenario. It begins with a small 1 t class lander delivering several small robots to one of the lunar poles. These robots work together to identify a suitable landing site for an upcoming 8 t human class lander. In addition to local reconnaissance, the small rovers gather science data, validate technologies and refine concurrent operations. This will be the first time ever that multiple robots will be working together in close proximity on another celestial body. The robots will practice servicing operations, scout the region for future crew/cargo landing areas, and deploy landing aides. All robots will send back to Earth a steady stream of engaging and informative data and video, including the descent and touchdown of future crewed/cargo landers. A crewed lunar flyby is performed, utilizing for the first time the cryogenic propulsion stage to leave the Earth's gravity well.

A year later, the human scale 8 t lander touches down at the site identified by the small robots. It is carrying a version of the mobility chassis used by the crewed small pressurized rover (Figure 7). There is also the potential of it carrying small communications relay satellites that are deployed in lunar orbit to enable better coverage of the poles before descending. The mobility chassis will operate in autonomous and ground supervised modes at speeds and ranges far exceeding any previous planetary surface rover, and is outfitted with enough energy storage to survive the 15-day eclipse period. It will also be outfitted with hundreds of kilograms of science instruments and manipulators. The vast science payloads, substantially increased speed and range along with the capability to survive lunar eclipse will allow it to traverse long distances away from the polar landing site to achieve regional exploration. In addition to its own science payloads, it will also be capable of transporting one or more of the previously delivered small robots as it explores which could be used for servicing and remote observation. This mobility platform will provide multiple partnering opportunities while substantially reducing risk for future exploration missions.

The lunar surface roving capability is augmented for a few years during this period by crewed missions to low lunar orbit that are testing the transportation systems as well as refining techniques for tele-operating the surface assets from low lunar orbit. This activity is analogous to operating rovers on the surface of Mars from Mars orbit, as eventually may occur during a Mars orbital mission. An opportunity during this period occurs for practicing lunar orbit rendezvous techniques with crew rated systems (such as ISS Exploration Test Module (ETM), alternate transportation systems, SEV/Ascent module prototypes). Extended tele-operations supported by the communication relays can be achieved by docking to these crew rated systems for periods beyond nominal crew capsule lifetimes (typically about 7-9 days in low lunar orbit). Docking to systems with additional habitable volume will allow for longer duration stays in low lunar orbit.

This period also offers opportunities for application of human exploration capabilities to non-exploration missions such as the deployment and servicing of space assets. These cis-lunar missions could be flown as separate missions to test and refine exploration systems that will provide proximity operations, rapid EVA, and robotic manipulator capabilities. These missions could include rescue of an older satellite to prevent it from contributing to the orbital debris problem and deployment/servicing of space telescopes.

The next segment of the lunar exploration phase begins a few years later. The robotic precursor work has incrementally built up confidence in operations and systems design in preparation for more aggressive lunar exploration with humans. Human Lunar Return (HLR) occurs at one of the lunar poles due to the favourable solar and thermal conditions, thus not exposing the systems to the harshest operational environment of a full approximately 15 day lunar night.

After the site on the Moon that will host HLR has been sufficiently investigated by the robots, the deployment of the large scale exploration infrastructure begins. The deployment of the pressurized rover and the crewed ascent module occur within a year of each other, thus increasing the potential to share systems development like Environmental Control and Life Support System (ECLSS), thermal and power. Several years after the initial robotic missions, but before the first crewed mission, a small pressurized rover and supporting power infrastructure are landed in the polar region by a large cargo lander and self-deploy. It arrives on the surface as directed by the robotically emplaced landing aides.

The small pressurized rover is initially tested, then sent on excursions (in a ground supervised mode) progressively further away from the landing location, beyond the range of the small robots, to identify opportunities and optimal paths that can be used by the humans on the first crewed mission. A year later, when the humans along with any critical spares arrive, the fully checked out rovers (original mobility chassis and the new small pressurized rover) are waiting for them. The crew then perform up to a 14-day mission (seven days planned), exploring the near polar region and practicing operations and contingency scenarios for upcoming traverses. Having two human scale rovers (one pressurized, one unpressurized) offers redundancy and rescue capabilities in the event one rover becomes non-operational. The crew leaves the surface at the end of their mission while the robots continue exploring before the next crew arrives, enhanced by portable utility pallets and cargo delivered by small landers. Six months later another small pressurized rover is delivered, autonomously deployed and tested, so that it can join the previously delivered mobility chassis and pressurized rover at the next crewed landing location.

The next crew arrives six months later and performs a 14-day mission using the extended range and duration resulting from coupling the small pressurized rovers to the portable utility pallets (Figure 8). A crew does not return to this location for a year as the small pressurized rovers, the servicing robots and the portable utility pallets perform extensive ground supervised exploration. Almost two years after HLR, a third crewed mission arrives at the pole, with the goal of lengthening the mission duration to 28 days. This cycle repeats for two more years, with each mission lasting 28 days, enabled by the mobile infrastructure meeting the crew at new polar region landing sites and delivery of logistics and science instruments by small 1 t landers. By the time the mobile infrastructure is near the end of its design life, humans have spent 105 days on the lunar surface exploring and tested key planetary surface capabilities and operations.

Deep Space Exploration

The Moon Next scenario offers the option of repeating the lunar campaign at the opposite pole or

Figure 8 – Humans Exploring the Lunar Surface

evolving into a more complex lunar exploration campaign similar to the ISECG Reference Architecture for Human Lunar Exploration[4] (which could include extended crew surface durations, delivery of nuclear fission power, etc.). But if Mars is the priority destination, then the strategy is to leave the Moon and venture into deep space as most Mars surface related risk reduction operations have been addressed in the lunar phase. This will require development of the DSH during the lunar phase which will challenge budgets, so the development of advanced propulsion during this period is not assumed in this scenario, which will limit the number of NEA targets available for the first mission and the capabilities that can be delivered at the destination. Before the NEA mission begins, the DSH will have to be launched with sufficient logistics, destination systems will be added for enabling exploration, and aggregation of chemical propulsion systems must be complete at the staging orbit. This process can be done via AR&D (current assumption), or crew flights can be added to facilitate the assembly and integration of the deep space vehicle stack. The mission crew launches and rendezvous with the vehicle stack and continues on a yearlong round trip mission that features one to four weeks at the target NEA. While at the NEA, the crew explores the NEA and performs mitigation research using the destination systems appropriate for the size and type of NEA visited. The vehicle stack then begins the return trip to Earth, with the crew directly entering into Earth's atmosphere, with the vehicle stack elements being disposed of along the way. Advanced propulsion will have to be developed before Mars missions can be considered, so the Moon Next scenario is less likely to achieve a Mars orbital mission before the Asteroid Next scenario, due to the time and resources spent on the Moon.

Key Feature Comparison

A comparison of the key features for the Asteroid Next and the Moon Next scenarios through the end of

Phase 3 (approximately 2035) is displayed in Table 3. A subset of the key technology areas are also shown in the table. Mars Surface is included to show how the scenarios develop technologies to enable these missions. Most of the titles are self-explanatory; however, a few needing explanations follow.

Advanced ECLSS

A goal of research in environmental control and life support systems (ECLSS) is to achieve a full closed loop system that can operate independent of consumable resupply and support. Current design and research in this area focuses on improving both oxygen and water recovery by technologies related to methane processing, solid oxide electrolysis, water retrieval from laundry and hygiene wastewaters, and processing of solid waste. Near-closed ECLSS would increase reliability & reduce logistics of largely existing ISS ECLSS technologies (~90% water recovery and ~50% oxygen recovery). Closed ECLSS would increase reliability & reduce logistics with advanced ECLSS technologies approaching 100% recovery for both water & oxygen.

Advanced EVA & Suit Port

Current research in advanced EVA systems includes the development of suits with rear entry capability and habitation system crew-cabin pressure matching for compatibility with suit ports. Suit ports add architecture flexibility by minimizing airlock operations and increased containment of potentially hazardous substances, for they allow crew to don EVA suits already attached on the exterior of habitation systems thus eliminating the need for traditional airlock operations. Block upgrades of the EVA suits will factor in requirements for small gravity field and hard vacuum atmosphere (e.g. lunar surface) and for intermediate gravity field and low pressure atmosphere (e.g. Mars surface).

Extreme Mobility

Past experience with crew mobility was limited to unpressurized rovers on the lunar surface for short stays. ISECG nations now face new challenges of working on the exteriors of satellites, on asteroid surfaces, on planetary surfaces for long durations, or providing access to lunar craters. Surface mobility systems allow for the movement of cargo, instruments and crew on the surface of an object or planetary body. Examples include roving, climbing, crawling, hopping or burrowing into the surface. Systems for moving cargo include prepositioning cargo for future human use, or repositioning payloads for re-use. Crew mobility aids expand crew range, speed and payload capacity while also providing power, habitation and environmental shelter.

	Asteroid Next	Moon Next	Mars Surface Technology Needs
Concentrated utilization of the ISS	X	X	
Demonstration of the ability to live without the frequent supply chain from Earth	X Cis-Lunar Phase	X Deep Space Phase	
Deep space habitat in Cis-lunar	X Cis-Lunar Phase	X Deep Space Phase	
Total days on Lunar surface, (# of missions)	0 (0)	105 (5)	
Total days at NEAs (# of missions)	60 (2)	8 (1)	
Key Technology "Pulls"			
Advanced in-space propulsion	SEP		SEP/NTP?
Advanced electric power	SEP Power (100s kW)		SEP Power (MW?)
Advanced surface power		Photovoltaic	Fission
Advanced ECLSS	Near-Closed ECLSS	Near-Closed ECLSS	Closed ECLSS
Long duration habitation & life support	X	X	X
Radiation protection & mitigation	X	X	X
Advanced communication	X	X	X
Advanced EVA & suit port	X	X	X
Extreme mobility		X	X
Dust management & mitigation	?	X	X
Surface operations		X	X
Advanced EDL			X
Advanced Thermal	- Adv Heat Shield - Zero Boil Off Cryogenics	- Adv Heat Shield - Zero Boil Off Cryogenics	- Adv Heat Shield - Zero Boil Off Cryogenics

Table 3 – Comparison of Key Features of Asteroid Next, Moon Next, and Mars Surface

V. DESIGN REFERENCE MISSIONS

Human missions to the various destinations will be designed to meet the objectives of participating agencies. In order to gain insights and a shared understanding of what it takes to explore the various destinations, the ISECG has identified several Design Reference Missions (DRMs). Each DRM captures the notional mission concept, including the capabilities required and the basic operational concept. DRMs are developed early because they are useful in identifying requirements, partner roles, and dependencies. The DRMs listed in Table 4 were used for purposes of informing the mission scenarios.

Asteroid Next Design Reference Missions	Moon Next Design Reference Missions
Deep Space Habitat Deployment	Robotic Precursor Mission
Robotic Precursor Mission	Crew to Low Lunar Orbit
Crew to Deep Space Habitat in E-M L1 – Short Stay	Crew to Lunar Surface – 7 day Sortie Mission
Crew to Deep Space Habitat in E-M L1 – Long Stay	Crew to Lunar Surface – 28 day Extended Stay Mission
Crewed NEA Mission using Advanced Propulsion	Cargo to Lunar Surface (small)
	Cargo to Lunar Surface (large)

Table 4 – Primary Design Reference Missions

The following figures show sample DRMs for the mission scenarios. Figure 9 presents the DRM for the deployment of the deep space habitat, which is used in the Asteroid Next. The Deep Space Habitat is launched on a single heavy lift launch vehicle, such as NASA Space Launch System (SLS) and delivered to EM L-1 from LEO using the Cryogenic Propulsion Stage (CPS). Figure 10 displays the DRM for a crew mission to the deep space habitat, assumed to be at E-M L1. The crew mission is also relying on a single SLS launch with the Multi-Purpose Crew Vehicle (MPCV) and its crew as the main payload. The CPS delivers the MPCV to EM L-1 from LEO. After the completion of the crew mission at the DSH, the MPCV service module performs the departure burn that brings back the crew to Earth.

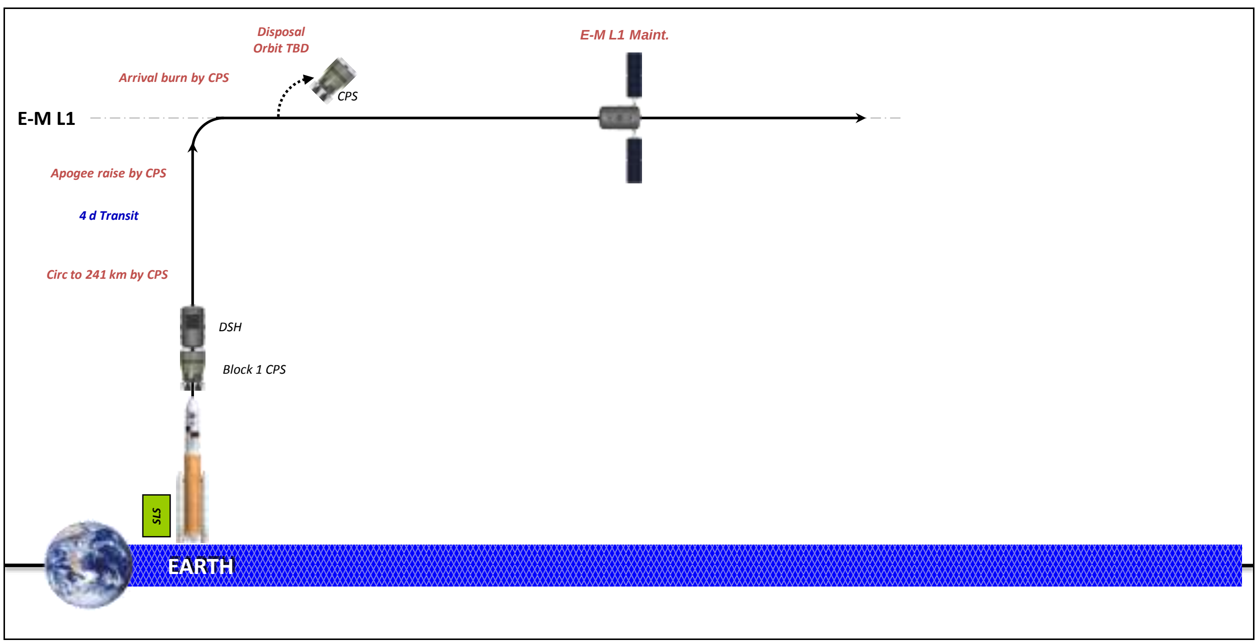


Figure 9 – Design Reference Mission for Deep Space Habitat Deployment

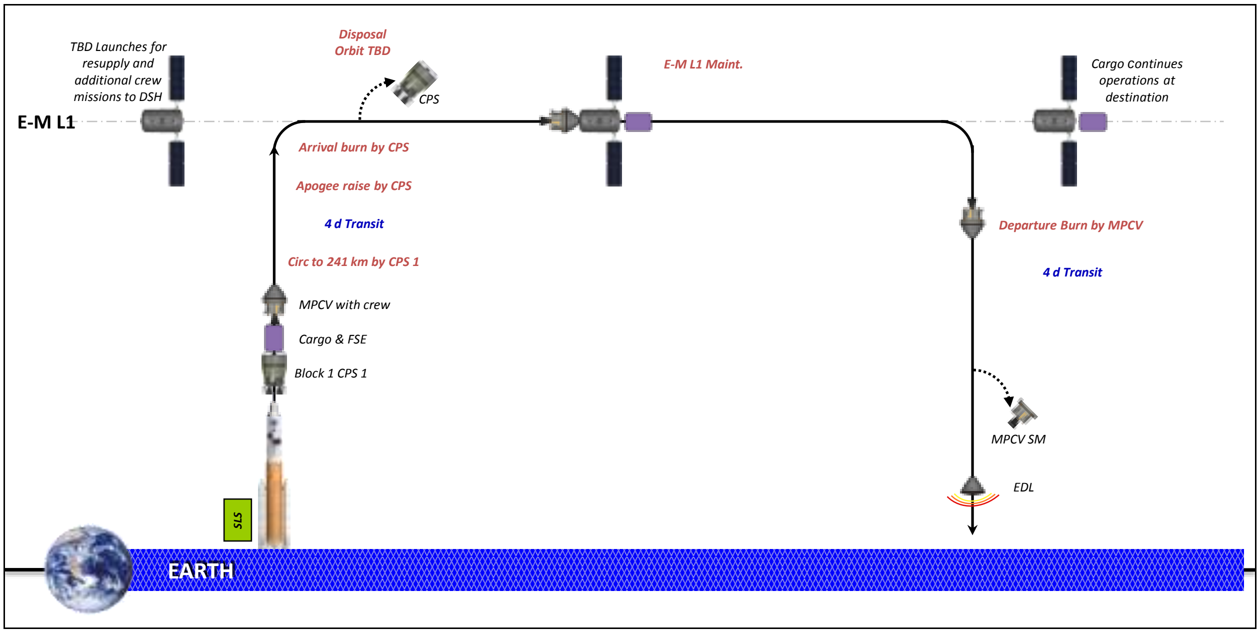


Figure 10 – Design Reference Mission for Crew Mission to Deep Space Habitat in E-M L1

Figure 11 depicts the DRM for the crew mission to a NEA, utilizing advanced propulsion. This DRM assumes Solar Electric Propulsion (SEP) for the advanced propulsion and is only applicable to the Asteroid Next scenario. The Moon Next scenario includes a crew mission to an asteroid, but does not assume advanced propulsion. This DRM is based on the assumption that the DSH previously launched, tested and commissioned at EM L-1 is used to perform the NEA mission. The DRM relies on the use of a combination of SEP and advanced cryogenic propulsion, zero-boil-off CPS (Block 2 CPS on Figure 11), to transport the crew and its associated systems to the targeted NEA and back. By using advanced propulsion, this DRM enables to reach a wider set of NEAs and to deliver more mass at destination, hence enabling crew to effectively address destination objectives. In particular this DRM portrays the Space Exploration Vehicle (SEV) that would provide crew with surface access while the MPCV and DSH stay in a safe orbit around the target.

Figure 12 portrays the DRM for a crew mission to the lunar surface and applies only to the Moon Next scenario given the current timeframe consideration. This DRM can be applied to either the 7-day Sortie mission or the 28-day Extended Stay mission. The lunar surface access DRM is based on a 2 SLS launch scenario with lunar orbital rendezvous. The first launch is used to pre-deploy in a Low Lunar Orbit (LLO) the human-rated lunar lander using a CPS for the transfer from LEO to LLO. A second launch of the SLS is used to deliver in a similar way the crewed MPCV in LLO. The MPCV and lunar lander perform docking in LLO. Then the crew transfer from the MPCV to the lander. The lander performs the descent and landing on the lunar surface. The crew can then perform its mission on the lunar surface supported by the lunar ascent vehicle and eventually additional pre-deployed assets. At the end of the surface mission, the crew return to the MPCV using the lunar ascent stage. Once the ascent stage is discarded, the MPCV Service Module performs the Trans-Earth Injection burn to put the crew module on an Earth-bound trajectory.

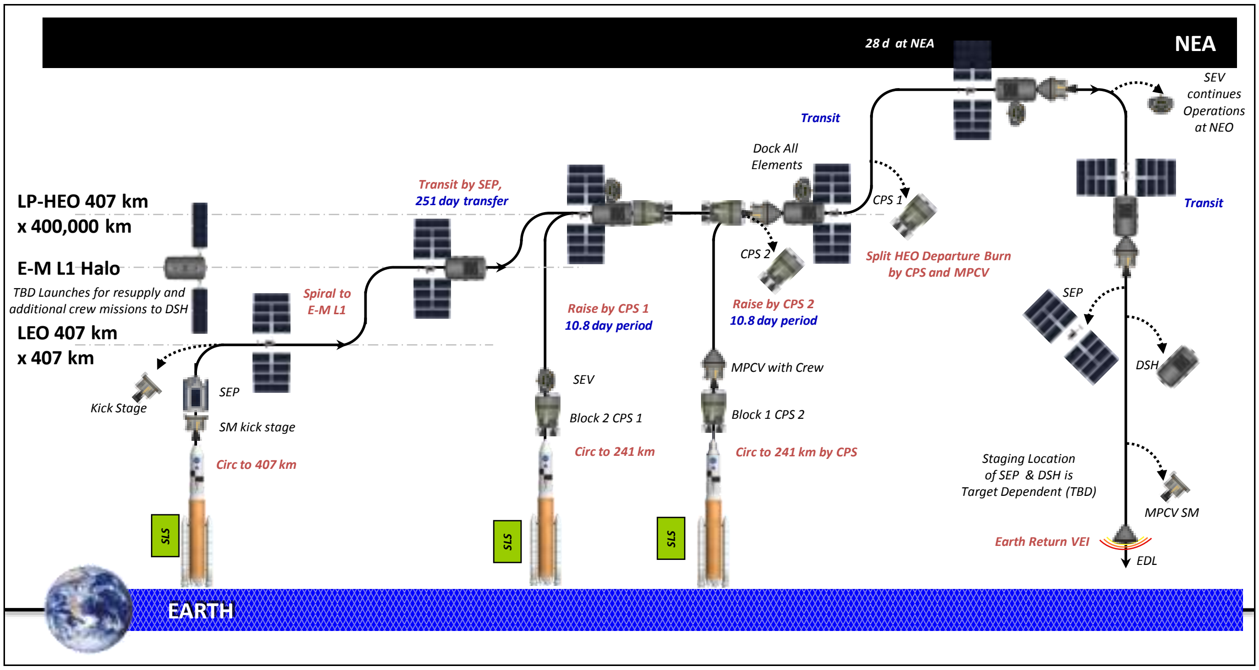


Figure 11 – Design Reference Mission for Crewed NEA Mission using Advanced Propulsion

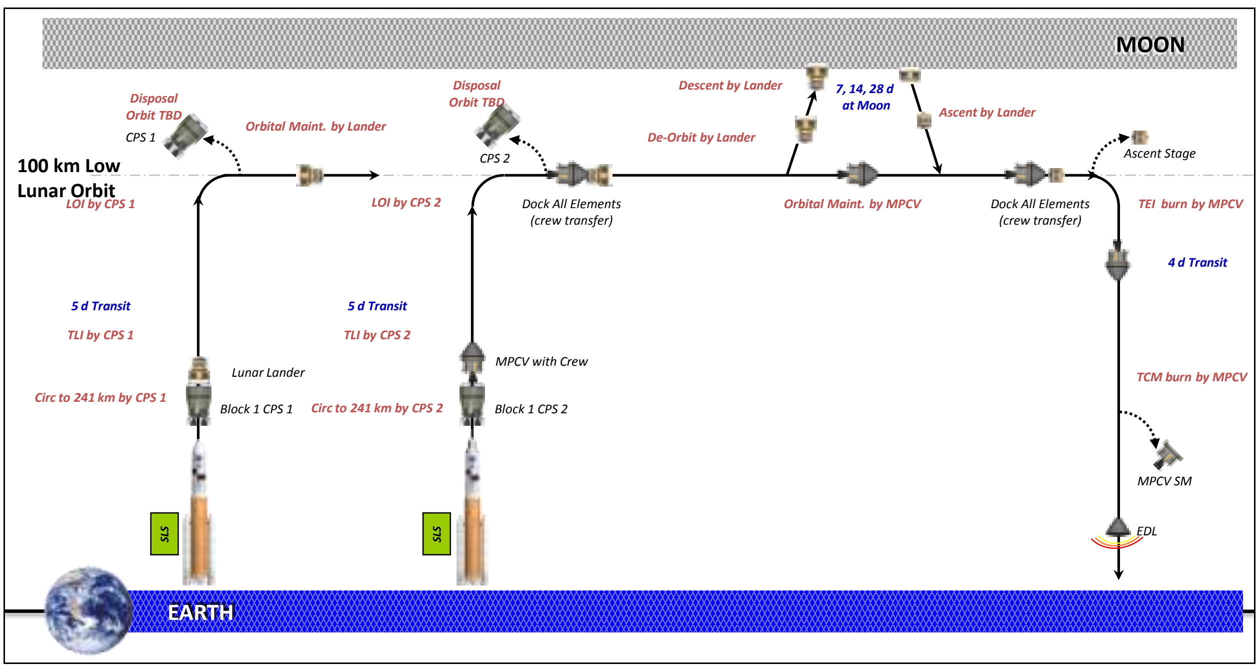


Figure 12 – Design Reference Mission for Crew to Lunar Surface

VI. MAJOR CAPABILITIES

Table 5 contains an overview of the major capabilities contained within the DRMs in the previous section. These definitions are high level and intended to provide the reader with an overview of the functions and key driving requirements of each capability.

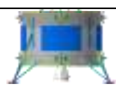
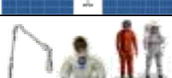
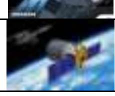
Icon	Capability Name	Description
	NASA Space Launch System (SLS)	Launch vehicle that has the capability to deliver cargo or crew from Earth to orbit. Assumed minimum net payload capability of 100 tons to SLS insertion point.
	ROSCOSMOS Next Generation Space Launch Vehicle (NGSLV)	Launch vehicle that has the capability to deliver cargo or crew from Earth to orbit.
	Cryogenic Propulsion Stage (CPS)	In-space stage that provides velocity increments to architecture elements using traditional chemical rocket engines and stored propellant (including cryogenics) and may include the capability for propellant transfer and zero oxygen boil off.
	NASA Multi Purpose Crew Vehicle (MPCV)	Crew vehicle capable of delivering a crew to exploration destination and back to Earth
	ROSCOSMOS Next Generation Spacecraft	Crew vehicle capable of delivering a crew to exploration destination and back to Earth
	Deep Space Habitat	An in-space habitat with relevant subsystems to sustain crew along their journey to distant destinations in a deep-space environment. Free-flying, independent of other systems for operations.
	In-space Destinations Systems	These systems have the capabilities that enable humans to effectively complete destination objectives by enabling crew access. Examples would include: robotic platforms, telerobotic platforms, EVA work systems, or combinations of these.
	1 metric ton Cargo Lander	System designed to land up to 1 ton on the lunar surface.
	Lunar Cargo Descent Stage	System designed to land payloads of up to 8 tons on the lunar surface, including the lunar crew ascent stage.
	Lunar Ascent Stage	Works in combination with the largest descent stage as a system for transporting crew to and from the surface of the Moon.
	Surface Elements	Capabilities that enable humans to effectively complete destination objectives by enabling crew access and EVA. Examples would include: robotic platforms, telerobotic platforms, EVA work systems, or combinations of these work systems. It also includes systems for power generation, ISRU, servicing, etc.
	Advanced in-space propulsion stage	In-space stage using non-traditional propulsion technologies, such as high power electric and nuclear propulsion.
	Servicing Support System	Systems and tools to enable crew and robots to service in-space systems and assemble larger capabilities, including EVA suits.
	Commercial Crew	Commercial system capable of taking Crew to Low Earth Orbit.
	Commercial Cargo	Commercial system capable of delivering Cargo to Low Earth Orbit.

Table 5 – Key Capabilities

VII. SUMMARY

To support the Global Exploration Roadmap, the ISECG has studied two mission scenarios in depth, Asteroid Next and Moon Next. A thorough description of each scenario has been discussed along with corresponding capabilities and applicable design reference missions. Subsequent iterations of the Global Exploration Roadmap will incorporate updates to these mission scenarios, reflecting updated agency policies and plans as well as consensus on innovative ideas and solutions proposed by the broader aerospace community. Ultimately, the roadmap will reflect the possible paths to the surface of Mars.

REFERENCES

[1] www.globalspaceexploration.org

[2] Hufenbach, B., Laurini, K., Piedboeuf, J., Schade, B., Matsumoto, K., and Spiero, F., “International Space Exploration Coordination Group – The Global Exploration Roadmap”, *62nd International Astronautical Congress*, Cape Town, South Africa, 2011.

[3] Matsumoto, K., Suzuki, N., Hufenbach, B., Piedboeuf, J., Carey, W., and Cirillo, W., “ISECG Space Exploration Goals, Objectives, and Benefits”, *62nd International Astronautical Congress*, Cape Town, South Africa, 2011.

[4] Culbert, C., Gonthier, Y., Mongrard, O., Satoh, N., Seaman, C., and Troutman, P., “Human Lunar Exploration: International Campaign Development”, *61st International Astronautical Congress*, IAC-10.A5.2.10, Prague, Czech Republic, 2010.