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COOPERATIVE SCENARIOS FOR HUMAN EXPLORATION BEYOND LOW EARTH ORBIT

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There is an international need to define a concrete strategy and plan to implement that strategy for the initial human exploration missions beyond Low Earth Orbit (LEO). Across all stakeholders, there is a growing consensus that the long term objective of global human space exploration is the long duration presence of people on the Martian surface. Along the pathway between current activities in LEO and eventual Mars outposts are a variety of preparatory exploration missions and intermediate goals. Over the last decade several different initial steps along these pathways beyond LEO have been proposed. It is important to build international consensus on such a plan soon because future missions require near-term investments for new capabilities with no single nation committing resources to achieve all the steps of an ambitious program on its own. The goal of this work is to enumerate and evaluate scenarios for cooperative missions beyond LEO that achieve incremental development of human exploration capabilities. Towards the goal of generating scenarios for cooperative missions beyond LEO, proposed missions and capabilities from a variety of international actors have been assessed. Presented in this paper are results of a survey of proposed missions and a series of interviews with industry experts knowledgeable about both the technical and geopolitical issues in forging a sustainable path towards Mars. There are four realistic proposals for initial human exploration beyond LEO: a cis-Lunar habitat, asteroid redirect, Mars flyby, and a Lunar surface sortie. In the absence of top-down agreements, such as those governing the International Space Station, that specify partnership responsibilities and privileges, ad-hoc exchanges within individual development projects or for specific mission capabilities is most likely to facilitate international cooperation in the coming years. General LEO transportation logistics and habitation functions are shared by many actors and allow for exchange of services and utilization of exploration assets if designed into the critical path. Given the early stage of readiness, it is possible that subsystem-level coordination could be pursued for an advanced habitation element. Other technologies are either niche (robotics) or have national sensitivities (in-space propulsion) that make them less desirable for subsystem-level coordination.

1. PLANNING AN INTERNATIONAL ENTERPRISE

Future human spaceflight programs need to be designed with sustainability in mind. A program that is both ambitious enough to foster broad support yet sized for realistic budgets will have to leverage international partners for cost and risk sharing. While there is a debate over the additional costs associated with international coordination and integration as compared to its cost-sharing and program sustainability benefits, the world's space agencies have said meeting the ultimate goal of Mars surface missions must be an international effort[*]. As individuals pursue the planning and execution of an exploration pathway from LEO towards Mars, they must consider both the technologies and the institutions that will bring humanity to this long term goal.

In August 2013 the International Space Exploration Coordination Group (ISECG) released an updated Global Exploration Roadmap (GER) [1]. The work of 12 space agencies, this roadmap provides a vision of the long-term goals and objectives for human space exploration. The GER details a number of missions that are preparatory for eventual sustained presence of humans on the Martian surface. Most importantly this roadmap reflects a cooperative relationship between several agencies that must work together to achieve any ambitious future exploration program. In the roadmap, the ISECG notes that the GER is published in the hope of eliciting a response from the "broader community." The specific contribution of the ISECG's work is intended to advance planning activities for international missions that will occur along the roadmap. The ISECG includes a set of missions that may be achieved in an international way, but stops short of suggesting how these missions will be coordinated and executed.

Towards the goal of building a sustainable exploration enterprise, we propose scenarios that trace mission technology needs to the capabilities of participating actors and the rationales for such contributions.

[*] Along with the ISECG, multiple experts groups and state policies have called for the necessity of international partners in future exploration programs. Some of these statements are found in the following references: [2], [3], [4], [5], [6], [7], [8], [9]

2. WHERE WE WILL EXPLORE

Proposals for human exploration missions between Earth and Mars include a variety of destinations and astrodynamic considerations. Proposed missions generally fall into one of three arenas distinguished by delta-v and mission duration. These are two of the primary mission requirements driving major architectural considerations for both transportation and habitation systems as shown in the figure below. Each arena may have several potential exploration destinations and associated missions to each destination. The resulting time of flight and orbital energy requirements for each exploration arena drive system mass, cost, and complexity. Between LEO and Mars lies a range of opportunities to pursue, incrementally proving out the capabilities needed for Mars. A strong development strategy will see evolution from one arena to the next, adding modest technical challenges at each step, but providing a consistent cadence of new exploration returns.

Lunar Surface

Lunar surface return was the focus for the exploration community through the 2000s and remains heavily supported by some individuals in the planetary science community as the appropriate next step in human exploration. Given the technical and programmatic challenges NASA encountered in the Constellation Program†, initial Lunar surface missions would likely involve a simplified architecture for sortie missions at near-equatorial regions to minimize design requirements on the lander. However surface presence may evolve to longer duration extended stay missions with increased surface access such as polar regions, depending on future budget commitments and technology developments.

Cis-Lunar Region

The cis-Lunar region extends between geostationary orbits and just beyond the Moon's orbit‡. Human or robotic infrastructure can be sent to halo orbits around the Earth-Moon Lagrange points 1 and 2 and other trajectories such as a lunar Distant Retrograde Orbit (DRO). These locations provide nuanced differences in exploration benefits but have similar delta-v requirements as compared to the other exploration arenas. Specific missions include the Asteroid Redirect Mission (ARM) and a cis-Lunar habitat with incrementally evolving capability for eventual long duration deep space habitation.

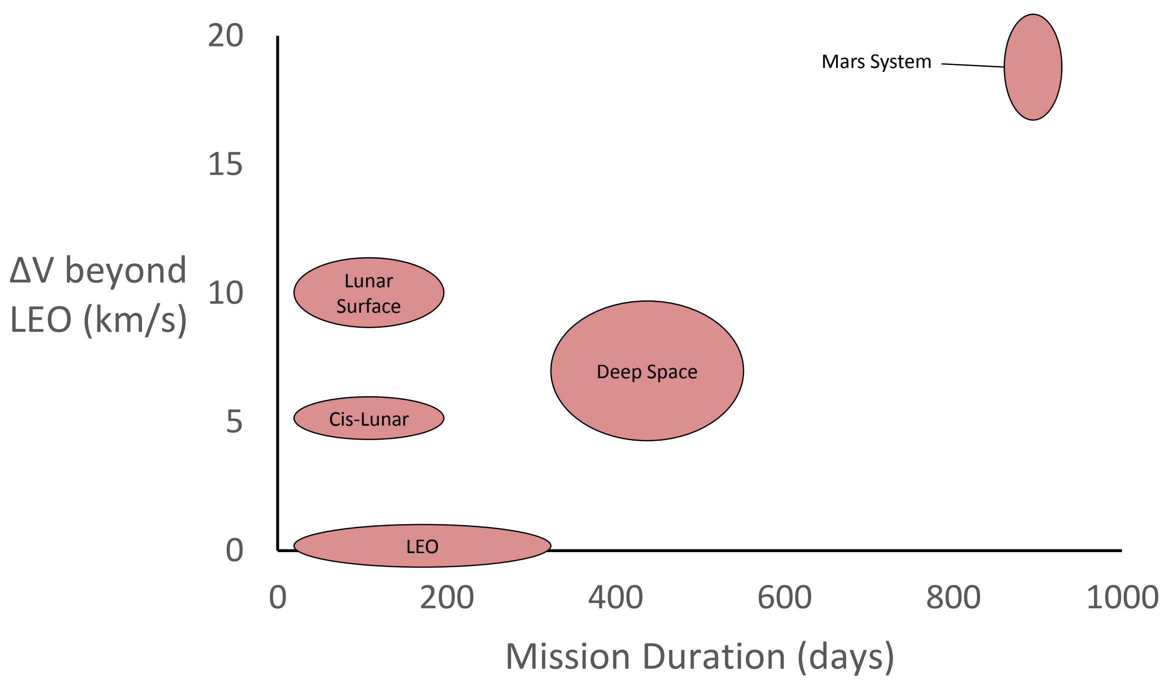

Figure 1 Exploration arenas distinguished by delta-v and mission duration

† The Review of Human Spaceflight Plans Committee documented the mismatch between exploration goals and allocated budget [15].

‡ While "cis-Lunar" often refers to the physical space between the Earth and the orbit of the Moon, in this context the definition is expanded to refer to orbits in the Earth-Moon system accessible at energy levels between Earth's gravity well and that of the Moon, including Lagrange points and Lunar Distant Retrograde Orbits.

Deep Space

This class of missions includes those that require escaping the Earth-Moon system on a heliocentric trajectory. In addition to increased delta-v and time of flight requirements, the lack of abort and contingency operations represents increased operational risk. Missions in this category include a Mars Flyby mission and asteroid rendezvous missions.

Mars System

Missions that require entering the sphere-of-influence of the Mars system include Mars orbit missions, rendezvous with one of the Martian moons, and various Mars surface missions. While some or all of these missions are likely to be accomplished along the pathway to Mars, they are the most technically challenging class of missions and are not considered as potential next steps in human exploration.

By categorizing proposed missions into possible options for next steps beyond LEO, and those intermediate missions that will come between next steps and the surface of Mars, a consolidated view of missions on the roadmap to Mars is provided below.

- Current Mission Capability: ISS (LEO)
- Next Steps: Cis-Lunar Habitat, Asteroid Redirect, Lunar Surface Sortie, Mars Flyby
- Intermediate: Mars Moons, Mars Orbit, Asteroid Rendezvous, Lunar Surface Extended Stay
- Goal: Mars Surface

3. EXPLORATION STRATEGIES

While there is general agreement on the need to define a roadmap from LEO to the surface of Mars, the pathway and strategy to traverse that roadmap is where opinions vary. Without trying to provide a comprehensive enumeration of theoretically possible sequenced missions, four strategic pathways begin with the four different “Next Steps” mission options. A more complete view of the pathways through various missions on the way to Mars is provided in Figure 2.

The missions in Figure 2 are organized according to two criteria. The vertical axis represents missions of increasing Technical Risk as measured by parameters such as delta-v, time of flight, and operational hazards. In the horizontal direction, missions are ordered by the number of technology developments they require that will not be used for eventual Mars exploration. Between missions the incremental unique development projects required to advance to the next mission are noted. For example the most direct and incrementally developing set of missions towards Mars represented are those on the left side of the figure (ISS→Cis-Lunar Habitat→Mars Flyby→Mars Surface). Pursuing these missions will produce new technology elements, all of which are used in eventual Mars Surface exploration. While an extended stay on the Lunar surface helps prove out several systems for Mars, it also requires a number of elements that will not directly support Mars exploration such as Lunar descent and ascent capabilities and so is located further to the right on the figure.

It is important to note that it is not necessarily “better” to pursue a pathway along the left side of the figure. Longer pathways to Mars will have more science return, and technology developments will reduce the risk of eventual Mars missions. There is a tension between following a plan with concrete milestones based on a set Mars transportation architecture, and maintaining the flexibility to incorporate technological improvements over time. A good example of this is that Solar Electric Propulsion (SEP) may not currently be specified as part of a minimalist architecture to Mars, but pursuing a path that develops SEP could demonstrate that it enables Mars architectures superior in performance and cost to reference designs based on current technology.

Using this view of potential pathways between LEO and Mars, we can look at the current set of human missions described by the ISECG Roadmap. The current GER outlines NASA’s planned asteroid mission, the general international interest in Lunar surface missions, and Cis-Lunar activities to develop deep space habitat capabilities. The GER makes no specific mention of human missions between Cis-Lunar space and eventual humans at Mars, although they do mention robotic precursors and technology demonstrators. It is unclear if the ISECG believes Lunar Surface missions and a deep-space habitat will provide sufficient risk reduction for Mars surface missions, or if they intentionally allow for uncertainty of mission selection as future technology challenges become better defined over time. Casting the current ISECG roadmap onto Figure 2 demonstrates a significant technical gap between Lunar Surface missions and Mars surface missions that could be filled by asteroid rendezvous or Mars orbital missions.

4. SUMMARY OF CAPABILITIES

To move towards evaluating contributions for international cooperation, a framework is provided to assess the likelihood of a nation’s contribution to an exploration program. By reviewing literature and surveying industry experts two major contributing factors were assessed: the technology readiness for a given nation, and the expected political commitment to that capability. These factors are intended to capture the industrial know-how and resources committed to completing development projects. The highest rating represents a capability that is available, while the lowest rating represents a capability not likely to be pursued for

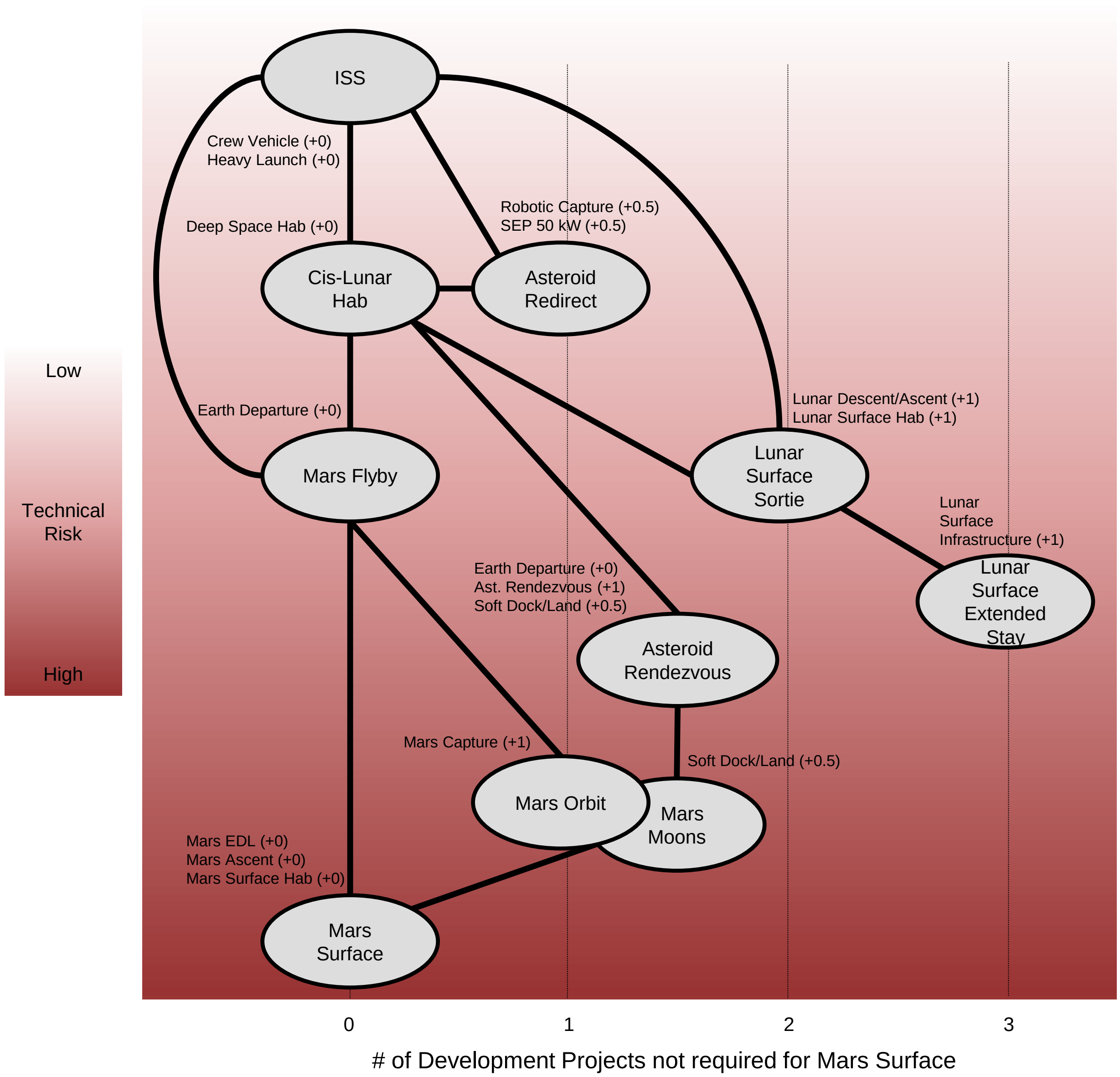

Figure 2 Enumerated likely mission milestone pathways through to Mars

a given country in the near term. Six national actors§ are considered: USA, Russia, Europe, Japan, Canada, and China, each of which have operational human spaceflight programs. Other nations are developing new capabilities and could play a role in future exploration efforts, but it remains to be seen exactly what capabilities they will develop in the coming years. A summary of the capability evaluation rubric is provided in Table 1.

Following are the evaluated capabilities of each nation as they relate to each of the four "next step" missions. Brief findings and observations follow for each of the missions. Initial Operating Capabilities (IOC) are required for initial deployment of the mission, while value-added capabilities represent elements that would increase the return of the mission, but are not part of a minimum viable system. Expected national contributions

§ In the context of the presented analysis national actors are an abstraction that includes the space agency, domestic contractors, research institutions, and political decision makers within a single nation. This level of abstraction is intended to capture the appropriate level at which major international agreements are set in motion. For the same reasons "Europe" is referred to as one of the six nations considered, as it is expected the relevant industry stakeholders will engage in international human spaceflight partnerships predominantly through the organization of the European Space Agency (ESA).

Table 1 Capability evaluation rubric

Rating	TRL Range	Readiness Description	Expected Commitment
●	8-9	Flight Readiness	Achieved capability, resources already spent
◕	6-7	Subsystem Integration	Likely capability, significant resources committed
◔	4-5	Concept Validation and Component Development	Early developments, some resources committed or strong strategic interest
○	0-3	Concept Development	Unlikely without increased resources and changed priorities

and the rationale for the mission are included after the breakdown of capabilities.

Cis-Lunar Habitat

Multiple concepts for a human-tended facility in the Lunar vicinity have been proposed for missions ranging in duration from several days to year-long profiles [2], [3]. The concept of the facility would most likely maintain a semi-autonomous predeployed habitat that has periodic crew visits (unlike the constant human presence on the ISS). A typical reference mission used has a crew of four for a 30 day stay; however, the capability of the facility could be scaled down or up as necessary due to program cost and schedule constraints. The concept for the facility would be to develop and prove out advanced life support systems for eventual long duration missions, while operating in a location that supports other activities such as telerobotic Lunar exploration and allows for quick return in abort scenarios.

Likely contributions for a cis-Lunar habitat include crew transportation systems from the USA and Russia. Logistics capabilities (delivery of propellant, cargo, and consumables) are available from USA, Russia, Europe, Japan, and China; however, the increased requirements on in-space transportation will require new in-space propulsion developments to deliver crew and cargo to the cis-Lunar habitat. The most significant opportunity for new technology development is in advancing the state of

Table 2 Cis-Lunar Habitat Capabilities by Actor

	USA	Russia	Europe	Japan	Canada	China
Initial Operating Capabilities						
Crew vehicle 11+ km/s re-entry	◕	◔	○	○	○	○
Crew-rated launch	◕	●	◔	○	○	●
50-70 mt launch	◕	◔	○	○	○	◔
Crew vehicle service module	◕	●	◕	◔	○	●
Large in-space propulsion (EDS)	◔	◔	◔	◔	○	◔
Automated rendezvous & docking	●	●	●	◔	◔	●
Pressurized hab & cargo	●	●	●	●	○	●
Advanced ECLSS	◔	◔	◔	○	○	○
Advanced radiation protection	◔	◔	◔	○	○	○
Value-Added Capabilities						
Human lunar landing	◔	◔	◔	○	○	○
Robotic lunar landing	◔	◔	◔	○	○	●
SEP 400 kW class	◔	◔	○	○	○	○
Cryo storage & handling	◔	◔	◔	◔	○	◔
Artificial gravity facility	○	○	○	◔	○	○
In-space robotic manipulation	○	○	◕	●	●	◔
Planetary surface robotics	●	◕	◕	◕	◔	●
Onboard science utilization	●	●	●	●	○	◔
Airlock/EVA	●	●	○	○	○	●

Table 3 Asteroid Redirect Mission Capabilities by Actor

	USA	Russia	Europe	Japan	Canada	China
Initial Operating Capabilities						
Crew vehicle 11+ km/s re-entry	◕	◔	○	○	○	○
Crew-rated launch	◕	●	◔	○	○	●
50-70 mt launch	◕	◔	○	○	○	◔
Crew vehicle service module	◕	●	◕	◔	○	●
Large in-space propulsion (EDS)	◔	◔	◔	◔	○	◔
SEP 50 kW class	◕	◔	◔	◔	○	○
Automated rendezvous & docking	●	●	●	◔	◔	●
In-space robotic manipulation	○	○	◕	●	●	◔
Asteroid capture	◔	○	○	○	○	○
Planetary surface EVA	◔	○	○	○	○	○
Airlock/EVA	●	●	○	○	○	●
Value-Added Capabilities						
SEP 400 kw class	◔	◔	○	○	○	○
Planetary surface robotics	●	◕	◕	◕	◔	●

ECLSS (environmental control and life support systems) and advanced radiation protection techniques. Advanced ECLSS with increased autonomy and system closure is in early development stages in USA, Russia, and Europe. Developing these systems will be a critical-path item on the way to Mars. Given the early stage of readiness, it is possible that subsystem-level coordination could be pursued for an advanced habitation element. Due to the cis-Lunar habitat's flexibility in operation, there are more opportunities for value-added activities from international contributors for the cis-Lunar habitat than any other next step mission. It is worth noting that half of the surveyed experts believed the cis-Lunar habitat should be the next mission pursued after the ISS.

The cis-Lunar habitat aligns well with the goals of multiple agencies, as it directly provides access or develops capability towards other future missions including both the Lunar surface and Mars missions. The cis-Lunar habitat also provides the most direct extension of both technology and organizational elements of ISS of all the proposed missions. One of the greatest challenges to developing the cis-Lunar habitat is communicating the benefits that lie in engineering development, as opposed to the exploration of a tangible rocky destination. In particular, while the cis-Lunar habitat may satisfy incremental developments towards national space exploration objectives, no current national space policy highlights this engineering development milestone as desirable to pursue on its own merits.

<u>Asteroid Redirect</u>

The Asteroid Redirect Mission (ARM) was made popular in recent years by a Keck Institute study on the feasibility of such a mission [4]. The overall concept is for an initial robotic retrieval mission that is linked to future human exploration. A solar-electric propelled (SEP) spacecraft will capture a small asteroid (or piece of one) and return it to cis-Lunar space (a Lunar DRO). Once there, it will provide a planetary surface that can be visited by a crew vehicle with lower delta-v penalty than any other rocky body. Recently NASA has engaged in a concerted architecture design effort to reduce some of the uncertainties of the mission implementation [5], [6].

The ARM is currently in development as a NASA mission, without planned partnerships at a level that would influence mission architecture. However, an agreement is already in place for ESA to provide NASA's crew vehicle service module that would be used for this mission. Other opportunities for ad-hoc inclusion of international partners are most likely to center on the Japanese and Canadian expertise in in-space robotic manipulation.

NASA's adoption of this mission presents a strategy focused on technology development. One of the most significant outcomes of this mission would be the realization of a 50 kW class SEP capability. Advancing state-of-the-art SEP will provide benefits to exploration, commercial, and defense communities. While low thrust propulsion has never been particularly attractive for crew transfer, larger SEP capability will provide great returns for cargo and logistics transfer for future deep space missions. Since the USA has the largest investments in future technologies, the mission has fewer opportunities for inclusion of international partners on the critical path. While the mission engages multiple stakeholder communities including planetary defense and some

Table 4 Mars Flyby Capabilities by Actor

	USA	Russia	Europe	Japan	Canada	China
Initial Operating Capabilities						
Crew vehicle 14+ km/s re-entry	◔	○	○	○	○	○
Crew-rated launch	◕	●	◔	○	○	●
100+ mt launch	◔	◔	○	○	○	◔
Crew vehicle service module	◕	●	◕	◔	○	●
Large in-space propulsion (EDS)	◔	◔	◔	◔	○	◔
Automated rendezvous & docking	●	●	●	◔	◔	●
Pressurized hab and cargo	●	●	●	●	○	●
Advanced ECLSS capability	◔	◔	◔	○	○	○
Advanced radiation protection	◔	◔	◔	○	○	○
Value-Added Capabilities						
Artificial gravity facility	○	○	○	◔	○	○
Onboard science utilization	●	●	●	●	○	◔
Airlock/EVA	●	●	○	○	○	●

planetary scientists, there has been little stated interest from policy makers from other human spaceflight nations. Participants of the industry survey did not see many opportunities for international participation in the mission and were more supportive of asteroid redirect as an added capability to a pre-existing Cis-Lunar Habitat.

Mars Flyby

The Mars Flyby reference mission is based on the architecture described by the Inspiration Mars Foundation [7], [8]. This mission involves two astronauts going on a 500 day deep-space mission with a single close approach of Mars. In terms of exploration return the crew of two will have 10 hours observation time within 100,000 km of Mars. The overall concept of the mission is a demonstration of advanced deep-space capability. The returns are in system development for deep-space human exploration and the milestone of actually putting humans in the Mars vicinity as an inspirational achievement.

The Mars Flyby mission represents the largest increment in deep-space exploration capability of all the next-steps missions considered. The published concept is conceived primarily as a NASA mission designed around SLS and Orion however the habitation requirements may look similar to an evolved version of the previously described cis-Lunar habitat. Development of such a module could provide opportunities for partnership for the ECLSS subsystems or habitat module.

Overall, the rationale for this mission is to accelerate the Mars program. With an accelerated development timeline to execute the mission within a five to ten year timeframe, the mission would likely require an increased development budget. In the survey of industry experts, the support for this mission among the international human spaceflight community exceeds that of the asteroid redirect; however, it is unclear what roles the international community may play. The simplicity of the mission profile results in fewer unique elements to distribute among partners. Furthermore, those supporting this mission as a next step believe it requires an increase in available budget to be feasible.

Lunar Surface Sortie

While a range of human Lunar exploration architectures have been proposed, as a "next step" mission the focus would be on a minimalist return. The rationale behind the mission would be to prove out exploration techniques for future Mars surface missions and initial developments would specifically avoid costly permanent infrastructure. A recent NASA architecture study describes the differences between short duration sortie missions and extended stay missions [9].

A minimalist Lunar Surface mission would provide short duration sortie missions at near equatorial landing sites. The US has had significant development for such a mission from both the Apollo and Constellation Programs. While the crew vehicle and heavy launch programs remain under development from the Constellation program in the USA, developments for landing systems never progressed beyond subsystem prototyping and concept development level. As a result, the elements required for in-space transportation, landing systems, and surface equipment would all be available as opportunities for contributions for international partners.

Due to the decades of development work, and opportunity for planetary science and commercial utilization, there is a large international advocacy for Lunar surface exploration. Due to the number of elements required for initial operating capability, the

Table 5 Lunar Surface Sortie Capabilities by Actor

	USA	Russia	Europe	Japan	Canada	China
Initial Operating Capabilities						
Crew vehicle 11+ km/s re-entry	◕	◔	○	○	○	○
Crew-rated launch	◕	●	◔	○	○	●
50-70 mt launch	◕	◔	○	○	○	◔
Human lunar landing systems	◔	◔	◔	○	○	○
Crew vehicle service module	◕	●	◕	◔	○	●
Large in-space propulsion (EDS)	◔	◔	◔	◔	○	◔
Automated rendezvous & docking	●	●	●	◔	◔	●
Pressurized hab & cargo	●	●	●	●	○	●
ISS class ECLSS	●	●	●	○	○	◕
Planetary surface robotics	●	◕	◕	◕	◔	●
Planetary surface EVA	◔	○	○	○	○	○
Airlock/EVA	●	●	○	○	○	●
Value-Added Capabilities						
100+ mt launch	◔	◔	○	○	○	◔
Robotic lunar landing systems	◔	◔	◔	○	○	●
Cryo storage & handling	◔	◔	◔	◔	○	◔
Advanced ECLSS	◔	◔	◔	○	○	○
Planetary surface robotics	●	◕	◕	◕	◔	●
Onboard science utilization	●	●	●	●	○	◔

Lunar surface provides the most opportunities for critical path contributions at the international scale. At the same time, development of all these elements result in a cost and risk profile unlikely to be supported by near-term budgets. Pursuing lunar surface missions would require efficient allocation of contributions across partners, and sustained if not increased development efforts from those partners.

Capabilities Summary

Figure 3 shows a summarized view of the capabilities required for each of the proposed missions and the aggregated readiness of those capabilities for each actor. Overall the cis-Lunar habitat and Mars Flyby missions require incremental advancement of existing transportation and habitation capabilities. Meanwhile the asteroid redirect and Lunar surface missions require significantly more new development projects.

Currently Russia and China are the only two nations with capability to put humans in LEO. It is expected that the USA will regain that capability in the next two to four years. Canadian and Japanese expertise in robotics are unique, and provide the capability for critical elements for in-space operations. These capabilities may extend to planetary surface exploration as developments to support cis-Lunar activities or Lunar surface exploration. In terms of human spaceflight, European contributions are focused on the habitable structures and logistics required for long duration missions. It is important to note that accounting for number of capabilities required is a proxy for the difficulty of development activities, but does not reflect the inherent risk associated with each mission. For example the number of technologies required for a cis-Lunar habitat is the same as that of a Mars Flyby mission, but the operational risk of the Mars Flyby is much greater than that for the cis-Lunar habitat considering the drastically different crew radiation exposure and abort opportunities.

Figure 3 demonstrates that there are significant gaps between current exploration capabilities and those needed for any next steps missions. To meet any of these challenges a significant amount of development work must take place. However there are limited development efforts for beyond LEO capabilities at an advanced stage in any actor other than the US as shown in Figure 4.

Despite leading in technology development, NASA's budget is unlikely to support more than one or two new major human spaceflight developments to completion beyond the crew and launch systems already in progress. While international contributor's budgets may increase provided appropriate justification, their contributions are more likely to evolve from existing capabilities than to begin new development projects from the ground up. Unlike most other actors, the Russian budget is expected to continue seeing moderate increases. Russia is currently

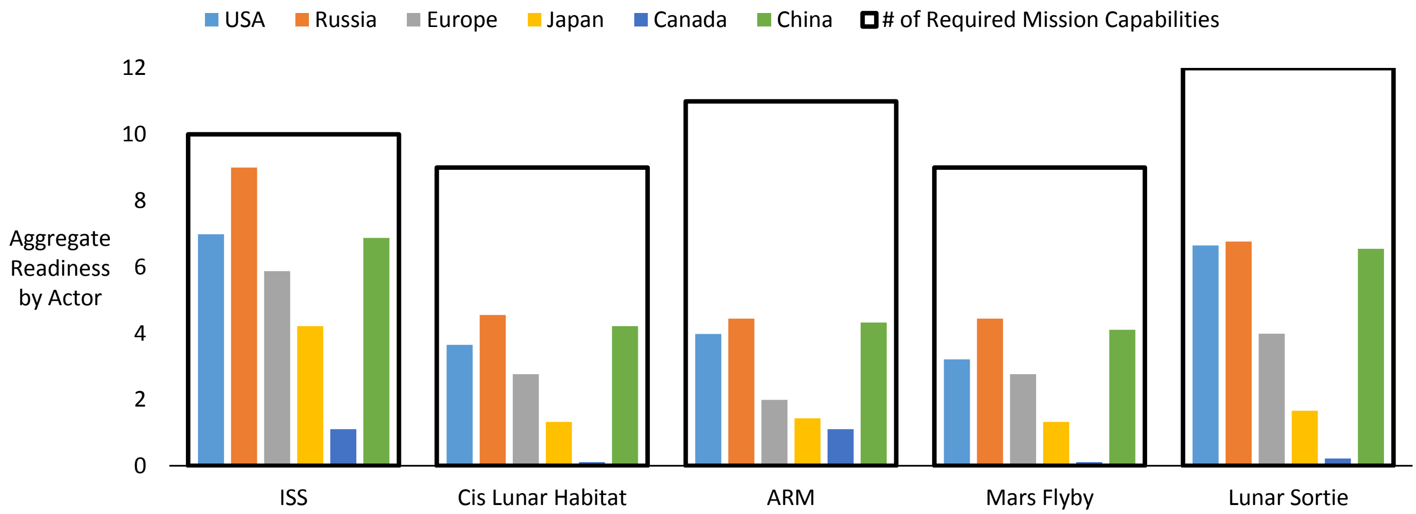

Figure 3 Summary of capabilities for each mission by nation

undergoing a national space industry reformation and is investing heavily in ground infrastructure developments. As such, it is unclear what development budget will be available for new technologies for human exploration beyond LEO.

While still a developing program, Chinese crew and transportation capabilities could offer crew-access redundancy and cost sharing in future projects. Large scale integrated collaboration for human spaceflight seems unlikely with the Chinese in the near term, as the Chinese program has an independent strategy for a LEO space station. However, opportunities for developing cooperative relationships in space should be pursued in smaller space missions to develop the working relationships that will open up more opportunities for integrated exploration activities. To date, European and Russian officials have opened discussion of collaborative efforts with China. While current US policy prevents NASA from coordinating with the Chinese, exploration advocates have begun to call for a change to these policies including specific guidance from the US National Research Council to consider US collaboration with China [10].

A sustained and robust beyond LEO human exploration program requires several large technology development projects that no single nation can develop in a reasonable timeframe. While Russia and China have independent human spaceflight capability, it is unclear that either program is committing significant resources to develop capabilities for beyond LEO exploration. Meanwhile the US program is investing in future projects but has yet to complete any capabilities that operate beyond LEO. A successful beyond LEO program requires some amount of cooperation between these independent human spaceflight programs.

5. ORGANIZING COOPERATION

The current organizational structure of the ISS has a hierarchy of agreements corresponding to coordinated efforts between governments, space agencies, and contractors. Overall cooperation agreements between governments are established through an Intergovernmental Agreement (IGA) that defines the overall nature of the partnership. One level down, agency coordination is executed through a series of memoranda of understanding (MOU). The MOUs are organized between NASA as a central entity and the other primary agencies dictating specific contributions, roles, and responsibilities. Other agency-level implementation specifics are coordinated on an ad-hoc basis through implementing agreements drafted as necessary. At the element level, development of specific modules and operations are coordinated through various contracting mechanisms by each participating agency within its own country.

The current framework in which ISS partners work together represents a decade of organizational development. There is broad agreement that human exploration beyond LEO should build on the relationships, experience, and institutions of ISS, but there remains a significant amount of ambiguity as to what specific aspects will most benefit future programs. In addition to extending previous experience, it is likely that future programs will have to be more flexible to incorporation of new actors. China is developing capabilities that may soon intersect with the needs of other partners beyond LEO, and other countries such as India, have stated their intent to pursue independent human spaceflight capability. Furthermore, several private companies have stated intentions to participate in future exploration efforts that could add a layer of complexity in new partnerships between state-run and private programs.

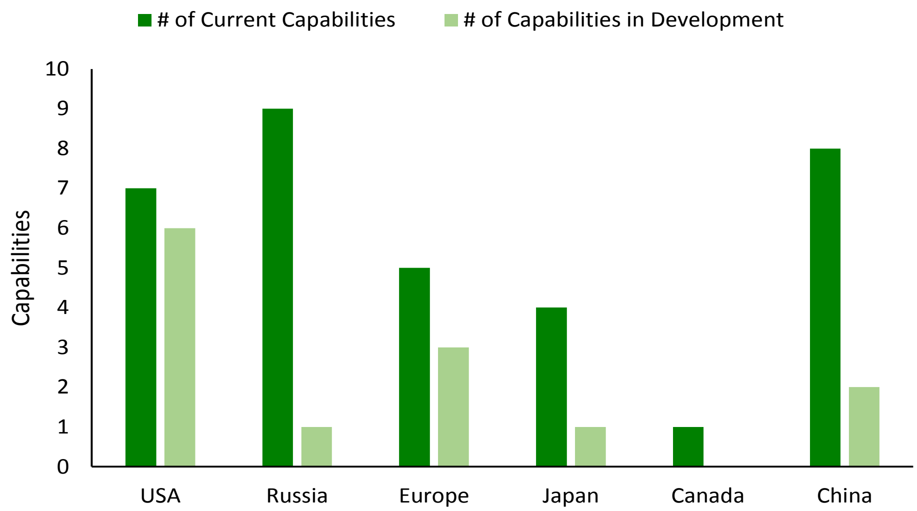

Figure 4 Summary of capabilities for human exploration beyond LEO by actor

While some literature exists describing different paradigms of cooperation in space exploration [11], there remains a need to consider how to categorize the organization of coordinated efforts for future human exploration beyond LEO. General discussion of building from experience at the ISS requires details of the agreements and organizational aspects that will or will not be useful beyond LEO. Furthermore, there are technical differences in exploration beyond LEO that may motivate a change in the organization of future programs. For example increased requirements in delta-v make mission feasibility much more sensitive to overall system mass. As a result, having multiple redundant and independently developed systems is unlikely to be feasible beyond LEO (as it has been for the ISS). In addition to reduced redundancy, there will be reduced frequency of flight opportunities and an increased risk environment requiring tightly coordinated system development and integration. Four possible organizational strategies are described below.

<u>Independent Programs</u>

Independent programs require nations to develop entire missions with domestic capabilities. While multiple nations have developed domestic programs in LEO, it seems unlikely that any nation will afford a sustained beyond LEO program without international contributions.

<u>Ad-Hoc Exchanges</u>

In the absence of top-down management and intergovernmental agreements that specify partnerships with responsibilities and privileges, ad-hoc exchanges within individual development projects or for specific mission capabilities is most likely to facilitate international cooperation. Ad-hoc exchanges best describe many efforts in robotic exploration missions where specific contributions are designated for a mission, and must be negotiated on a case-by-case basis. The European service module for the NASA crew vehicle is the first example of a cooperative agreement that builds on an ISS obligation to fulfill a beyond LEO capability[**]. It remains an open question if a human spaceflight enterprise can be sustainable without a higher level of coordination. For example, as exploration continues with ad-hoc exchanges, an organization such as the ISECG may have to evolve to play a more significant role in planning the missions that will be pursued as opposed to their current role where its work reflects mission decisions already made by national agencies.

<u>Integrated Agreement Structure</u>

An integrated agreement structure for exploration beyond LEO would replicate or adapt the hierarchy of agreements in place that organize the ISS. This would involve an agreement between governments of the overall exploration goals and partnering nations, and cooperation between agencies as to the responsibilities of each nation. One of the largest changes in moving to beyond LEO exploration is that future mission capabilities and destinations are uncertain and will change from one mission to another as compared to a LEO facility with consistent system architecture. While individuals argue for defining a set pathway of missions towards Mars, the reality is that engineering development is uncertain, and the exact roadmap between LEO and

[**] ESA's Orion Service Module is based on their Automated Transfer Vehicle (ATV) and is part of the barter agreement with NASA covering a portion of ISS operating expenses through 2020. This involves both an agency-to-agency and company-to-company agreement.

Mars can not be established with certainty. An integrated framework for cooperation beyond LEO requires a mechanism to adapt planned contributions as milestones are met and capability needs evolve.

Multinational Entity

Just as ESA coordinates space efforts from across Europe, a multinational intergovernmental entity could collect resources to implement the global human space exploration enterprise. This level of integration and loss of autonomy for national agencies is unlikely to occur as the decision to commit to exploration budgets is a national process tied to many domestic concerns. At the national level decision makers are unlikely to give up the ability to control their space budget because they have rationales that may not align with those of a multinational entity. ESA has addressed this problem by having some mandatory contributions and separate elective programs in which nations can choose to participate[††].

6. SCENARIOS

Scenarios that dictate what may be accomplished in the next steps of human exploration beyond LEO are driven by two factors: resource commitment and the cooperative environment of human spaceflight. Following are some of the factors that will result in a low or high level of resource commitment, and a low or high level of cooperation on beyond LEO exploration.

The most likely scenario is that major national human spaceflight budgets remain fairly flat. If budget increases are lower than inflation, there is a consistent loss of purchasing power over time. Even when interest in government spending on space is high, it is difficult to justify the long-term uncertain returns of human spaceflight developments as compared to the concrete benefits of ground infrastructure improvements and programs with more commercial interest relating to navigation, earth observation, and telecommunications services. For example while Russia has committed to a multi-year increase in overall space spending, it remains to be seen what specific developments will be supported for human spaceflight beyond LEO. A more optimistic scenario would see government spending increase as part of a commitment to a robust human exploration program. Alternatively, resources could become available from private-sector entities that decide to start spending significant resources on human exploration beyond LEO.

The current cooperative environment for space is dynamic and uncertain in the future. Development and operation of the ISS has succeeded in part due to the ability of participating agencies to work together. Despite recent geopolitical tension outside of the space industry, all currently operating projects in space science and human exploration continue, seemingly unaffected by these external factors. However individual politicians have made statements indicating space cooperation could be limited in the future. While no operating cooperative agreements have been hindered, at a practical level this political tension may make it more difficult to engage in the early discussions and planning required to create proposals for future cooperative efforts. Aside from the geopolitical issues, cooperation could be limited by differing goals. While all agencies have agreed on Mars as the eventual goal, China and Russia have both clearly stated they intend to pursue Lunar surface exploration first. Meanwhile the USA has pursued an asteroid-centered exploration strategy on the way to Mars. The third issue that could make cooperation difficult, is the desire for nations to maintain fully independent-operating exploration capabilities. In the case of the ISS, having independent crew systems allowed for a design with redundancy. However for more technically challenging missions beyond LEO, it may prove cost prohibitive for two nations to provide independent transportation and habitation capabilities.

Four scenarios are described as a set of possible outcomes dictated by the levels of resources committed and the cooperative environment.

Scenario A: Low Resources, Low Cooperation

The current stated plans of the USA, Russia, and China reflect a reality of limited cooperation and flat or modestly increasing budgets. The USA is pursuing the asteroid redirect mission. While ARM is still being formulated, international partners have not yet been engaged in early rounds of goal setting and mission architecture design. If development is delayed too long or suitable targets are not identified, the USA will have to resort to flying short duration Orion missions with little opportunity to practice astronaut-conducted science operations. Russia and China will continue to slowly develop their independent efforts towards Lunar surface exploration. Europe, Canada, and Japan will continue to contribute niche elements to other human spaceflight programs, however if milestones are not met or astronaut flight opportunities are not available in return, they may lose political support and redirect their human exploration budget to endeavours with more quantifiable return on investment.

Scenario B: Low Resources, High Cooperation

With modest resources available, human spaceflight programs will seek to build off the developments of ISS. In a highly cooperative environment, the USA, Russia,

[††] Note that projects within ESA might be better categorized as "ad-hoc exchanges" or "integrated agreement structure." These categories provide a way of thinking how nations may collaborate but are not necessarily strictly implemented within a single category.

Europe, and China could all contribute to development of a cis-Lunar habitat facility. Pursuing this platform does not have to be mutually exclusive from the USA pursuing the ARM on its own; it would depend on the available budget and the specific role outlined for the USA in the habitat project. If both ARM and a cis-Lunar habitat are planned to be operational at the same time, they can be designed to be mutually beneficial. A redirected asteroid would provide a location for astronauts to practice new EVA techniques, with the opportunity to develop operations over longer duration missions coming from the cis-Lunar habitat. Meanwhile it is possible that the ARM's SEP spacecraft bus including power, propulsion, and thermal subsystems could in fact support the cis-Lunar habitat as primary or backup modules in future operations. To enable this vision of integrating the ARM and cis-Lunar habitat, planning would need to occur in the near future, before the system architecture of ARM is defined.

Scenario C: High Resources, Low Cooperation

With a drastically increased budget, the USA can pursue ARM while developing a large upper stage for SLS and possibly a deep-space habitat. The date of initial operating capability would be sensitive to the size of the budget increase and corresponding schedule advancement. Meanwhile China and Russia will commit large resources to the lunar surface and these programs will develop with little ability to interact or interface. Europe, Japan, and Canada may provide elements to the other three programs in exchange for astronaut time and scientific equipment utilization.

Scenario D: High Resources, High Cooperation

In the case where funds are available and multiple nations are contributing to a coordinated program, more ambitious missions are possible. With multiple nations committing to develop new technology elements, it may become worthwhile to pursue a coordinated effort to the Lunar surface so that commercial and scientific interests can reap benefits while later on engineering development continues on deep-space habitation and transportation. This scenario can only be realized if nations commit to providing costly development projects that are interdependent on each other on a strict schedule.

7. SUMMARY AND CONCLUSIONS

The ISECG activity provides a valuable arena for developing common understanding of future exploration initiatives. The GER includes expected missions from national efforts and a set of milestones that may be accomplished with international support, but stops short of suggesting how these milestones will be achieved. To benefit from international cooperation, nations seek to be responsible for elements that are in the critical path and are integral to the success of a sustained program with frequent highly visible milestones. Coordinating those international efforts requires concerted and authoritative planning activities at the international level.

There are four realistic proposals for initial human exploration beyond LEO: a cis-Lunar habitat, asteroid redirect, Mars flyby, and a Lunar surface sortie. Summarized rationales and challenges of each mission are provided in Table 6.

The contributions of new development projects from each participating nation will be limited and sensitive to future budget allocation. While the USA currently has the largest portfolio of investments for beyond LEO capabilities, it is unable to afford development of all capabilities required. Planning now can help increase the cost sharing for future integrated exploration efforts. Given the early stage of readiness, it is possible that subsystem-level coordination could be pursued for an advanced habitation element. Other technologies are either niche (robotics) or have national-interest sensitivities (in-space propulsion) that make them less desirable for subsystem-level coordination. General LEO transportation logistics and habitation functions are shared by many actors and allow for exchange of services and utilization of exploration assets if designed into the critical path.

In the absence of top-down management and an IGA that specifies partnerships with responsibilities and privileges, ad-hoc exchanges within individual development projects or for specific mission capabilities is most likely to facilitate international cooperation in the coming years. In particular future exploration institutions should be flexible to adapt contributions depending on what is learned from early missions to prove out deep space systems. Furthermore future programs will benefit from having the flexibility to incorporate new state and private actors.

It is unlikely that development for human exploration beyond LEO will receive drastically increased resources in the near future. Given the modest development budget available globally, nations must plan now for closely integrated mutually beneficial projects. If the USA pursues the ARM, mission planners must coordinate with potential partners so that the spacecraft development provides value as part of an ongoing program to develop deep space capabilities.

Table 6 Overview of "Next Step" strategies

Next Step Mission	Summarized Rationale	Summarized Challenges
Cis-Lunar Habitat	– Continue habitation developments from ISS – Provide access/developments for all other destinations – Hab developments are required for Mars – Provides opportunity for contributions from all partners	– Not stated in existing policy – Poor perception of mission without a rocky destination – Science returns only possible with coordinated efforts on the Moon (or a redirected asteroid)
Asteroid Redirect	– Advance solar electric propulsion (SEP) capability for many customers (not just exploration) – Potentially engages planetary science & defense stakeholders concerned with asteroids (opinions vary) – Provides highly visible exploration firsts	– No developments that build on ISS habitation capabilities. – Unclear if developments are useful for Mars. – Few feasible targets identified. – Few opportunities for non-US on the critical path
Lunar Surface Sortie	– Strongest science engagement – Strongest supported destination among non-US stakeholders (and some groups in the US). – Best place for surface operations prep	– Requires the most new (and costly) developments before initial operating capability. – Feasibility is unclear without increased international contributions. – Unclear if Lunar developments are on the critical path to Mars.
Mars Flyby	– High profile achievement to foster increased support – Fastest path to Mars surface	– Limited science return – The highest level of overall development and operational risk.

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