Contents lists available at ScienceDirect

Reviews in Human Space Exploration

journal homepage: www.elsevier.com/locate/reach

Enabling innovative research on the International Space Station to solve the challenges of a human mission to Mars: Results of the ISS4Mars international workshops 2020–2021

Michael Waid[a,*], Livio Narici[b,c], Michaela Girgenrath[d], Katrin Stang[d], Isabelle Marcil[e], Perry Johnson-Green[e], Thu Jennifer Ngo-Anh[f], Oleg Kotov[g], Keiji Murakami[h], Robert Dempsey[a], Jancy McPhee[a], Kevin Sato[i], Bette Siegel[j], Sam Scimemi[j], Julie Robinson[j]

[a] *National Aeronautics and Space Administration (NASA) Johnson Space Center, 2101 NASA Pkwy, Houston, TX 77058, United States*
[b] *Italian Space Agency (ASI), viale del Politecnico, Rome 00133, Italy*
[c] *University of Rome – Tor Vergata, via della Ricerca Scientifica, Rome 00133, Italy*
[d] *German Aerospace Center (DLR), Koenigswinterer Str. 522-524, Bonn 53227, Germany*
[e] *Canadian Space Agency (CSA), 6767 route de l'Aéroport, Longueuil, Quebec J3Y 8Y9, Canada*
[f] *European Space Agency (ESA), P.O. Box 299, Noordwijk 2200 AG, The Netherlands*
[g] *Institute of Biomedical Problems (IBMP), Russian Academy of Sciences (RAS), Khoroshevskoe 76A, Moscow 123007, Russia*
[h] *Japan Aerospace Exploration Agency (JAXA), Sengen2-1-1, Tsukuba, Ibaraki 305-0052, Japan*
[i] *NASA Ames Research Center, P.O. Box 1, Moffett Field, CA 94035, United States*
[j] *NASA Headquarters, 300 E Street SW, Washington, DC 20546, United States*

ARTICLE INFO

Keywords:
Human space exploration
Mars risk mitigation
Deep space mission analog
Integrated mission testing
Low Earth orbit

ABSTRACT

During the ISS4Mars workshops in 2020–2021, personnel from the International Space Station (ISS) partner agencies convened to reflect on scenarios for how the ISS could be used and its operations possibly modified to simulate aspects of a human mission to Mars. Scientific leaders, operations experts, crewmembers, managers, and flight surgeons discussed the five hazards of human spaceflight—gravity transitions, radiation, isolation and confinement, distance from Earth, and hostile closed environments—and considered how an ISS-based analog of Mars transit could benefit assessments and mitigations of these hazards. A focused writing team then discussed the advantages and disadvantages of each approach identified by the workshop participants before developing a set of eight use cases to consider the feasibility of implementing on the ISS. The writing team also identified the prerequisites needed, including ground analog studies simulating a mission to Mars required to verify measurements and procedures, before testing could begin on the ISS. Five of the use cases were considered feasible to assess in simulations using an ISS-based analog of Mars transit if some ground rules and assumptions were met. These five use cases were Earth-independent medical operations, Earth-independent integrated operations, life support and food for a one year duration, lower-body negative pressure as a countermeasure against the effects of exposure to microgravity, and fitness levels after landing. In addition, three more extensive interventions—extended Mars surface operations, a small-volume transit analog, and artificial gravity—were deemed unfeasible for testing on the ISS. Experience gained from the five use cases executed on the ISS may help answer some of the questions in the deferred scenarios, or it may be possible to complete them on another platform (e.g. commercial space station, lunar habitat). Simulating conditions during a Mars mission on the ISS will afford higher fidelity for assessing multiple integrated hazards of human spaceflight, however, ground analogs of Mars missions can be used to ensure effective measures and experimental design before testing begins on the ISS. The strategic concepts refined as part of these workshops were brought to a multilateral forum, Mulitlateral Human Research Planel for Exploration (MHRPE), where ISS partner agencies are now discussing implementation plans to provide new opportunities to use the ISS to prepare for deep space exploration over the coming decade. In this publication we present a summary of the international strategic plans for future research that will enable opera-

---

[*] Corresponding author.
E-mail address: michael.c.waid@nasa.gov (M. Waid).

https://doi.org/10.1016/j.reach.2022.100047
Received 27 January 2022; Accepted 8 August 2022

tions, software, and countermeasures to be developed that will reduce the risk to humans during future crewed missions to Mars.

1. Background

Over the past two decades, the International Space Station (ISS) partners have used the ISS for three main research goals: (1) as a laboratory for conducting controlled experiments in life and physical sciences in microgravity conditions, (2) as an analog to understand the effects of weightlessness on human physiology by studying the crew while they live and work on board the ISS, and (3) as a platform for making observations using instruments from space [1]. A significant amount of research on the ISS now focuses on understanding and mitigating the effects of microgravity on astronaut health and performance in preparation for a successful future microgravity transit to Mars [2–4,43,47].

1.1. Overview of exploration-related research on the ISS

In the past, effects of spaceflight stressors have been characterized individually. However, in recent years, both the National Aeronautics and Space Administration (NASA) [5,6] and international spaceflight partners [7–10,49] have begun a broader and more integrated consideration of all the different hazards that a crew would experience on a Mars mission (Table 1), and whether those challenges are similar to those on the ISS, or could be simulated on the ISS.

1.2. Why ISS4Mars?

Deep space human exploration beyond Earth's vicinity is probably the greatest and most complex endeavor in human history. Scientific and technological advancements on the ISS, and in spaceflight more broadly, will pave the way for a future crewed mission to Mars, although mitigating the effects of some spaceflight hazards still requires significant research [3,31].

New technologies, countermeasures, and operations for a Mars mission can be assessed, and scientific investigations [44] can be performed in analogs of the spaceflight environment if these spaceflight analogs have the appropriate fidelity. The ISS international partners have developed a strategic framework that considers every spaceflight as an analog with some level of fidelity for a Mars mission (see Fig. 1, [5]). Although many valuable research studies are conducted in ground-based analogs of spaceflight [32–35,45–46,52], these "space" analogs provide lower-fidelity than flight platforms. The ISS has been used effectively to model microgravity-induced physiological stresses that will occur during a transit to Mars. Temporary changes in ISS operations could simulate various additional aspects of a Mars mission, such as the challenges of communication outages [36] and latency, and an increased level of crew autonomy [37]. These ISS modifications could be used to assess important operational challenges prior to testing during lunar missions [42,51], which will have even higher fidelity but be more hazardous. Evolving paradigms of ISS operations could thus enable the success of future exploration missions. To address this opportunity, interagency discussions were initiated to develop a more intentional, collaborative, and operationally focused ISS-based analog of Mars, dubbed "ISS4Mars".

Table 1
Grouping of major hazards [5,11,12] that present risks to humans during deep space missions. The risk examples are not always aligned with only one hazard.

Hazard	Examples of Major Risks to Humans
Altered Gravity Fields: microgravity, partial gravity, and transitions between gravitational fields	Bone fracture [13], reduced muscle size, cardiac rhythm problems, renal stone formation, host-microorganism interactions [14], sensorimotor alterations [15], orthostatic intolerance, spaceflight associated neuro-ocular syndrome (SANS) [16], cardiovascular adaptations [17], reduced aerobic capacity [17], urinary retention, reduced ability to egress the vehicle
Radiation Exposure: acute and chronic [18]	Radiation carcinogenesis [19], cardiovascular disease [20], alterations in the central nervous system changes [21,22,23], immune function [24], and reproductive system [25]
Distance from Earth: communications delays, blackouts, inability to evacuate	Inadequate inflight medical responses [26,50], inadequate food and nutrition [27,28], ineffective and toxic medications, inadequate human systems integration architecture, inadequate responses to emergencies
Isolation and Confinement	Inadequate psychosocial adaptation within a team [29], adverse cognitive or behavioral conditions [30]
Hostile Closed Environments:	Exposure to toxins, celestial dust [53], and elevated carbon dioxide levels [54,55], hypoxia, decompression sickness, reduced performance during extravehicular activity [56], altered immune response [56,57], electrical shock, sleep loss, hearing loss, injury from dynamic loads

1.3. Workshop purpose and goals

Representatives from some of the ISS partners agencies met in Rome, Italy in October 2018 to participate in the first ISS4Mars workshop. The full history of the conference and the discussions are reviewed by Robinson *et al.* (2021) [38]. Because ISS partner space agencies expressed interest in discussing innovative approaches to conduct strategic operational, medical, and experimental studies on the ISS (and future low Earth orbit platforms) in preparation for human missions to Mars, a second ISS4Mars Workshop[1] was conducted with international partners. The second ISS4Mars workshop first convened in October 2020, and the final products resulting from this workshop were completed in October 2021.

The second ISS4Mars workshop offered an opportunity for participants with a wide range of backgrounds in implementing research on the ISS to consider additional approaches that could help prepare for future exploration missions—studies that were not being proposed because they did not fit in the current confines of research conducted on the ISS. The aim of the workshop was to obtain structured responses to the following 3 key questions and to seek recommendations for new and innovative uses of the ISS as an analog for Mars missions.

- *What added value does an ISS-based analog of Mars transit provide compared to ground analogs of spaceflight environments and conventional studies on the ISS?*
- *How technically feasible would it be to implement Mars analog simulations on the ISS without impacting other research on the ISS?*
- *What synergies exist with other objectives such as the visibility of the ISS to the general public, extension of the ISS operations, and developing of commercial economy in low Earth orbit?*

---

[1] The workshop was co-organized and -hosted by the ISS partner space agencies, Italian Space Agency (ASI, Rome, Italy), Canadian Space Agency (CSA, Longueuil, Quebec, Canada), National Center for Space Studies/Institute for Space Medicine and Physiology (CNES/MEDES, Toulouse, France), German Aerospace Center (DLR, Cologne, Germany), European Space Agency (ESA, Noordwijk, Netherlands), Institute of Biomedical Problems (IBMP)/Roscomos (Moscow, Russia), Japan Aerospace Exploration Agency (JAXA, Tokyo, Japan), and National Aeronautics and Space Administration (NASA, USA).

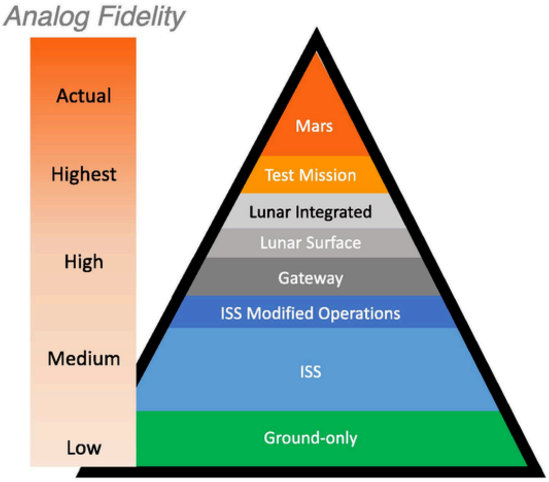

Fig. 1. Strategic framework to prepare for a human mission to Mars in terms of the overall fidelity of the spaceflight analog, as well as the access and ease of conducting research (width of the triangle).

The workshop participants reviewed the challenges of exploration missions, developed recommendations for temporary changes in ISS operations that could simulate those challenges, and provided suggestions on how to implement these changes. The workshop was essentially an interagency meeting intended to identify the rationale, implementation approach, and impacts of concepts for using the ISS as an exploration analog.

1.4. ISS4Mars workshop structure

Due to the pandemic, the organizers planned a virtual format that took advantage of the potential benefits of remote assemblies as summarized in Fig. 2. Part I included plenary talks from representatives of each space agency, followed by breakout group meetings that each addressed a key hazard associated with crewed missions to Mars (Table 1), and participants addressed modifications to ISS operations that could address these challenges. After part I, the organizing committee identified an international writing team comprising technical and scientific experts from ASI, CSA, DLR, ESA, and NASA, to refine the work of the breakout groups, develop use case scenarios, discuss operational practicalities, determine good experimental design, and assess how to implement the approaches. The workshop participants then reconvened in part II of the workshop to discuss the use cases and the perspectives of different stakeholder groups. Finally, the writing committee further consolidated, reviewed, and refined the use cases, made recommendations of ground rules and assumptions for implementation, and wrote this final report with additional support from IBMP and JAXA. A more detailed description of the workshop structure can be found in Robinson *et al.* (2021) [38].

2. Findings and recommendations from ISS4Mars workshop part i

In total, nine breakout meetings (Table 2) were conducted to thoroughly examine the five hazards listed in Table 1. The participants of each breakout session considered two questions specific to the hazard they were reviewing: “What are the key challenges of exposure to this hazard during a Mars Mission?” and “How could the ISS be modified to help address or simulate these challenges?” The topics of the breakout sessions overlapped considerably. For example, communications delays can affect medical operations, and they can also contribute to the effects of isolation and confinement. Radiation was not considered as an independent topic. Because radiation exposure might magnify the effects of other issues that were explored, the workshop participants considered radiation exposure only when relevant. The findings and recommendations of the breakout sessions are provided as expert opinions without full annotation of the references and the previous research that may have been on the minds of the participants during their discussions.

Summaries of the recommendations resulting from each of the 9 breakout meetings are provided sections 2.1. to 2.8. below.

2.1. Critical hazards during transit to Mars and associated countermeasures that would benefit from testing in an ISS-based Mars transit analog

The participants of this breakout meeting deemed several critical hazards to crewmembers’ health as high priority for study using an ISS-based Mars transit analog. These health hazards included exposure to microgravity for the same durations expected for transits to and from Mars; behavioral challenges associated with long-duration isolation and changes in circadian rhythm; and retention of mental and physical proficiencies throughout the mission. The participants agreed that effective

Fig. 2. ISS4Mars workshop process and structure. MHRPE is the Multilateral Human Research Panel for Exploration, a group that discusses human research strategy and implementation between ISS partner agencies. GR&A indicates ground rules and assumptions.

Table 2
Topics discussed in each breakout meeting.

Primary Hazard	Focus of Discussions	Section
Altered Gravity	Critical hazards during transit to Mars and associated countermeasures that would benefit from testing in an ISS-based Mars transit analog	2.1
Altered Gravity	Gravity transitions and early surface operations for a Mars mission	2.2
Enclosed Environment	Living in a closed environment—Environment and closed life support systems	2.3
Enclosed Environment	Living in a closed environment—Food systems	2.4
Enclosed Environment	Living in a closed but leaky environment—Human microbiome, microbial monitoring, and planetary protection	2.5
Isolation and Confinement	Isolation and confinement	2.6
Distance from Earth	Medical operations for Mars missions	2.7
Distance from Earth	Autonomous systems and crew-centered autonomy	2.8
Distance from Earth	Communications delay effects on operations	2.8

Table 3
ISS4Mars use cases and recommendations from the focused writing team.

Use Case	Assessment	Section
Earth-independent medical operations analog	Recommended	3.1
Earth-independent integrated operations analog	Recommended	3.2
Earth-independent ECLSS, food, and autonomy analog	Recommended	3.3
Lower body negative pressure countermeasure analog	Recommended	3.4
Post-landing surface fitness analog	Recommended	3.5
Isolation/confinement research analog—transit	Deferred, challenges 1,2	–
Isolation/confinement research analog—post-landing surface	Deferred, challenge 3	–
Artificial gravity countermeasure analog	Deferred, challenges 1,2, and 4	–

Challenges: 1—too challenging to currently be implemented on the ISS, 2—dependent on Commercial low Earth orbit infrastructure that does not yet exist, 3—dependent on results of post-landing surface fitness use case, and 4—dependent on scientific flight data that does not yet exist.

countermeasures must be developed to maintain and enhance crewmembers' physical performance and to protect them against radiation exposure, and that the crewmembers must maintain a healthy diet.

The session participants emphasized that developing, testing, and validating countermeasures call for innovative thinking outside of the medical and scientific mindsets currently in use for the ISS. An example of this type of shift in mindset is a transition from a single organ-oriented protective approach to an integrated countermeasure approach for physiological systems. In addition, the participants recommended validating new countermeasure regimes using classical countermeasure studies on board the ISS and in ground-based analogs of spaceflight (e.g. bedrest studies and Antarctic research studies) before integrated simulations are conducted on the ISS. The panel also considered artificial gravity as a potential countermeasure to the effects of microgravity; however, they concluded that significant research was still needed to characterize how exposure to microgravity affects human health. Even if artificial gravity were implemented during travel to the Moon or Mars, crewmembers would still be exposed to partial gravity when living and working on the surface.

2.2. *Gravity transitions and early surface operations for a Mars mission*

The participants of this breakout meeting discussed the challenges crewmembers will face when they transition from microgravity to Mars gravity and perform early surface operations just after landing on Mars. The group noted that the expected transition between microgravity and partial gravity (gravity on Mars is 3/8 that of Earth gravity) will be novel for the sensorimotor system. When the crew lands, no ground team will be on Mars to support them. During an emergency, individual crewmembers may be required to perform physical tasks, and their response could be hampered if they are physically deconditioned from extended exposure to microgravity during the transit to Mars. The group regarded spaceflight-associated neuro-ocular syndrome (SANS) associated with extended duration in microgravity [16] as an additional issue of key importance.

Assessments of ISS crewmembers' performance on Earth after spending many months in orbit have provided insight into the challenges unaided crewmembers will face when they land on a planetary surface [39]. The participants of this breakout meeting suggested the following studies. ISS crewmembers who return to Earth on the Soyuz or future U.S. Commercial flights can be studied to further assess the effects of gravity transitions, and these crewmembers could provide an opportunity to test new candidate countermeasures. A Mars landing simulation conducted during the first few days of return from the ISS could characterize risks of Mars-relevant tasks—from landing to first Extravehicular Activity (EVA). The tasks performed could include lander egress, an emergency EVA, and manual control such as for telerobotics after landing. Some tasks also could be performed in simulated 3/8 gravity. To simulate the autonomy crews will face after landing on Mars, landing operations after return to Earth from the ISS could be modified to include monitored crew autonomy, increased privacy (e.g. no TV cameras or film crews), no immediate return to Johnson Space Center, and self-administered sensorimotor rehabilitation.

The session participants also suggested other uses of ISS to test potential Mars-relevant sensorimotor countermeasures, including (1) mimicking exploration-class exercise and balance training using the hardware and integrated data architecture that will be available on Mars vehicles, (2) using vestibular stimulations (e.g. galvanic) to precondition the vestibular system, accelerate the adaptation process, or correct the interpretation of vestibular queues, and (3) implementing artificial gravity via short-arm centrifugation.

Some attendees of this session proposed that a human-rated centrifuge was the best countermeasure to mitigate microgravity effects on the vestibular system and to prevent SANS; however, many open questions remain about the use of centrifugation to simulate Earth gravity: Would centrifugation add additional gravity transitions? Could exposure to intermittent bouts of artificial gravity delay adaptation? What about artificial gravity after landing? One of the main reasons why a centrifuge would be difficult or impossible to implement on the ISS is that the centrifuge diameter is too large to fit into an ISS module. Other technical issues of implementing artificial gravity were also identified. The session participants concluded that artificial gravity would be the hardest countermeasure to implement, and thus reasoned that other options to mitigate the effects of microgravity may be more practical, such as lower body negative pressure (LBNP) concepts (e.g. low-pressure level, longer duration) as a viable solution for preventing SANS and orthostatic intolerance.

2.3. *Living in a closed environment—Environment and closed life support systems*

A significant challenge for a mission to Mars is the number of spare parts that will be required, especially for maintaining the Environmental Control and Life Support System (ECLSS) [40]. Engineers have been able to reduce the required number of spare parts by 30%, which reduces the launch and landing weight of the vehicle but also requires the ECLSS to be more reliable. The participants of the breakout session determined that it is essential to conduct long-term tests of the Mars transit vehicle ECLSS in a relevant integrated microgravity environment. Because two-way communications delays between Earth and crews of

Mars missions can be up to 40 min (20 min to Earth from Mars and another 20 min back from Earth to Mars), processes must be in place for crews to autonomously maintain, troubleshoot, and repair the ECLSS system.

During this breakout meeting, the participants identified several concepts for using the ISS to address key concerns and issues related to the ECLSS and overall concerns about living in an enclosed environment. Their suggested modifications to the ISS included (1) adding a new module to the ISS where integrated testing of exploration system technologies can be performed, which may require different interfaces and thus necessitate hardware modifications; (2) conducting a trade study to identify the lowest mass necessary for the ECLSS and then using ISS to test this ECLSS with an exploration food system that has lower water content; and (3) using the ISS to test supplemental food production during a transit to Mars.

2.4. *Living in a closed environment—Food systems*

To address key challenges of the food systems for a Mars mission, the participants of this breakout meeting made a set of assumptions about the mission: (1) for the transit phase, they assumed the mass trades would be between shelf-stable and refrigerated food and a set of food production technologies not yet developed, such as bulk foods (bulk ingredients that must be assembled and cooked to prepare meals), 3D printing, and fresh grown foods; and (2) for a 30-day stay on the Mars surface, they assumed the surface food system would be a combination of prepackaged food and, if feasible, items prepared by the crew during their transit. Many, but not all these techniques are currently being tested on the ISS.

The meeting participants identified numerous key challenges, such as limited food stowage, support resources and capabilities, and food preparation equipment, and the challenge of providing a variety of food-types. The mass restrictions and the limited resources that will be available during a transit to Mars are major issues. Because all food must be either brought on the mission or prepositioned on a preparatory flight, food products must be shelf stable. Food must also be nutritious, high quality, and of sufficient quantity, with no risk of loss, to support the safety of the crew. Cold stowage allows more variety in supplemental foods, but cold stowage technology needs to be more efficient before it could be implemented on a Mars mission. Stowage modularity is also important so that not all food is ruined if one unit fails. Food preparation and support equipment must also be efficient. A warmer and a water dispenser would be useful to increase the variety of food options. All these requirements are difficult to achieve in an enclosed environment. The panel agreed that technology demonstrations for food preparation or storage and supplementary systems could be performed on the ISS. As a starting point, these new technology demonstrations could be integrated on board the ISS using existing units such as the ISS plant growth systems.

Food variety and quality supports health and enhances the astronauts' quality of life during a spaceflight. To help prevent crewmembers from developing adverse cognitive or behavioral conditions and psychiatric disorders, and to prevent boredom with the food (i.e., menu fatigue) during a Mars mission, the appropriate food quantity and variety needed to support crew preferences must be determined. In addition, because the crew of a Mars mission will not have constant contact with ground support personnel on Earth, new tools will be needed to enable the crew to monitor and manage dietary intake in support of their health and performance needs.

The participants of this breakout meeting determined that the ISS could be used to study and validate food for a one-year transit to Mars because the ISS provides a relevant spaceflight environment with microgravity and radiation hazards. To determine how a Mars mission food system impacts crewmembers' health and performance, the whole crew must consume realistic Mars mission meals, and the crew should have less food items to select from than the large number of preference items offered to ISS crews today. This simulation would allow researchers to study trade-offs between food stability and crew preferences. The meeting participants also suggested providing some ISS crewmembers with a Martian surface diet for 30 days, either as a standalone study or as part of a broader Mars surface analog study after an orbital ISS mission. However, due to the various technical challenges of enrolling crewmembers for long studies after they return from the ISS, the panel acknowledged that a 30-day food test in orbit would be more feasible, whereas a post-landing study would be quite difficult to design and complete.

2.5. *Living in a closed but leaky environment—Human microbiome, microbial monitoring, and planetary protection*

During this breakout meeting, participants identified key challenges of a predominantly closed but not perfectly sealed environment during a human mission to Mars. They determined that one of the major challenges would be conducting microbial monitoring of the environment and of the human microbiome to detect undesirable changes due to the prolonged, isolated transit or to the potential entry of novel Mars microbes into the vehicle. Monitoring technologies can be used to assess the extent to which the vents and the seals of pressurized modules leak microbes of human origin into the Mars environment. Also, supplies that may be pre-positioned on Mars or on un-crewed vehicles may also have to be assessed to determine changes in microbiology over time.

The participants of this session determined that microbes could be monitored before and after routine closure of ISS segments (e.g. the Pressurized Mating Adapter or the Bigelow Expandable Activity Module) as an analog for changes that might occur in un-crewed vehicles sent to Mars. They also concluded that the monitoring frequency of crew and the ISS should be substantially increased as part of ISS operations, and that standardized operating procedures and tools should be developed for sampling microbes in or on air, surfaces, water, and food, and in human samples.

2.6. *Isolation and confinement*

The key issues associated with isolated and confined crews include social and sensory monotony and boredom. Because a limited volume for both privacy and team cohesion will be available to the Mars mission crew, compatible crews should be carefully formulated to minimize interpersonal friction. Current countermeasures may also be inadequate and inefficient to combat new and non-anticipated psychosocial risks. Crewmembers of a Mars mission may find it harder to cope with separation from their loved ones because of the extended communication delays. It will be difficult for the crewmembers of a Mars mission to maintain performance through all three long-duration mission phases (outbound, surface, and return), and each phase may require different countermeasure approaches. Ground support personnel will also face new demands (e.g. Mars sol day length is different from Earth day). Therefore, investigators should also assess the unique challenges to the ground support teams.

The participants of this session concluded that the ISS could be used as an analog of the isolation and confinement during Mars missions if the ISS mission design and other factors were modified. For instance, the duration of ISS missions could be lengthened, crew autonomy increased, and ground-based monitoring and audio and video links reduced. The windows on the ISS could be blocked so the crew cannot view the Earth, as would occur during a Mars mission. Communication delays could be implemented, including increasing the delays in communication with family and with ground support personnel. Astronauts could be co-located in a habitable volume similar in size of expected volumes in the Mars transit vehicle. Changes to the crew schedule might include fewer tasks, to simulate periods of monotony and boredom. Both ISS crew and ground support personnel could follow a Mars sol schedule. The participants also agreed the operational performance measures, behavioral assessments, and individualized prescription assessments should be developed using ground simulations of spaceflight conditions before testing begins on ISS.

2.7. Medical operations for Mars missions

The participants of this breakout meeting identified the following key challenges of medical operations during a Mars mission: (1) communications delays will prevent the Mars crew from having real-time private medical conferences, private psychological conferences, health monitoring, and screening exams with ground support personnel; (2) providing medical care will be challenging because of the increased duration and complexity of a Mars mission, as well as the mass and volume constraints for medical systems and consumables; (3) increased EVA frequency on the Mars surface could lead to greater injury rate; (4) the prolonged and extreme isolation and confinement during a Mars mission could result in psychological effects; (5) exposure to altered gravity will induce physiological effects; and (6) crew will be exposed to deep space radiation.

Mars missions will require a completely new paradigm compared to the medical care on ISS missions today, including increased autonomy, reduced access to real-time ground support, limited resupply options, and the inability to evacuate to Earth. The crew of a Mars mission must be more self-reliant for medical care than current ISS crews, and they must be able to aggregate and use health data on board in a real-time fashion. A Mars Crew Medical Officer (CMO) must have more advanced medical skills and training than current ISS CMOs. The focus on prevention and early anticipation of medical issues must be increased; these areas are currently not well researched. Also, clinical skill retention during the mission will need to be fostered. These steps will help compensate for the lack of possible timely access to Earth-based medical support due to real-time communications delays.

The breakout group concluded that the ISS could be used to develop, test, and implement new methods and procedures for medical operations, and they provided the following suggestions. To increase medical autonomy on board the ISS, simulations could include physician astronauts who would have more delegated power to perform medical activities that might otherwise be the domain of the ground-based flight surgeons. ISS onboard capabilities for medical skill training and skill retention could be developed, including the ability to perform self-guided procedures for complex medical tasks. Simulated integrated medical scenarios in which the crew must function more autonomously for extended periods of time could be used to determine if the medical system will function effectively on a Mars mission. The following concepts could also be used on the ISS to assess medical operations for a Mars mission: testing an automated health monitoring system that uses artificial intelligence; simulating limitations in resupply (medications, food, consumables); increasing integration of medical operations between all international partners; and aggregating relevant health and performance data on board the ISS for astronaut use and decision making with limited ground support. All these simulations would require the development of onboard medical databases, health records, and decision-support tools.

The participants provided additional ideas to consider if using the ISS as a Mars medical analog: (1) extend the durations of ISS missions for an entire crew (i.e., from the nominal six months to a year or more); (2) prioritize research that explores medical unknowns and Mars needs; and (3) redesign an ISS module to include a Mars medical workstation for testing and validating new medical technologies and procedures.

2.8. Autonomous systems and crew-centered autonomy, and communications delay effects on operations

One of the most significant and common challenges identified during the breakout meetings was the communication time delays that will occur during a mission to Mars. Two individual breakout groups focused specifically on the effects that communications issues will have on crew efficiency, such as completing vehicle tasks, and on cognitive and psychological factors. The outcome of both these breakout sessions are described here; however, many of the factors below could also be included in the other ISS4Mars type of mission scenarios discussed earlier.

The participants of these two breakout meetings concluded that communication time delays can be implemented during ISS operations, as has been tested in a limited capacity in the past [41], and they suggested the following simulations. The crew and mission control can practice efficient pre-packaged communication to support crew activities using limited communication time or with large delays. A simulation of Mars mission equivalent communication delays can also be applied to interactions between ISS crewmembers and their family members, to simulate additional challenges. The communication delay scenarios could also reflect the altered patterns of work sharing between the crew and the ground support that will be required during a Mars mission. Connection rates could be adapted to match Mars scenarios, including the amount of link time. Simulating key aspects of the anticipated Mars mission workload, and thus psychological fidelity, will be important. The day on ISS could be aligned with a Martian day, and the crew work schedule could simulate potential impacts on crew sleep cycle and resulting performance. A simulated exploration Mission Control Center (MCC) that is separate from the normal real time ISS MCC would likely be needed to conduct these communication delays safely and effectively.

To simulate greater autonomous operations, ISS operations could be modified such that the crewmembers perform onboard training, apply decision support tools, plan tasks, etc., without the assistance of the MCC. Communication will be more effective if crews receive refreshers regarding what to expect and how to self-prepare for Mars mission communication delays.

3. Defining use case scenarios and ground rules and assumptions

After the breakout sessions concluded, a focused writing team developed a series of use cases and associated ground rules and assumptions that incorporated the findings from the first part of the workshop (see Fig. 2). During follow-on discussions, the workshop participants evaluated these use case scenarios and suggested specific Mars simulation concepts, feasible implementation plans within the framework of ISS standard operations, innovative ideas for expanding ISS capabilities to support the use cases, and international partnerships. A total of eight use cases were studied and developed; however, after more in-depth evaluation, the workshop participants determined that three of the use cases were too challenging to currently implement on the ISS (see Table 3).

The writing team also generated a set of ground rules and assumptions to aid in developing, reviewing, and implementing the use case scenarios, and to ensure crew health and safety during the use case activities. These ground rules and assumptions are as follows: (1) the crew will be briefed on and committed to mission parameters before the mission; (2) flight, medical, or crew operations personnel can stop the test at any time; (3) current processes for ensuring crew well-being through regular check-ups will continue; however, if a communication delay is imposed during the study, the checkups will occur with the imposed delay; (4) the crew will be provided countermeasures, including Mars-relevant and established protocols for treatment of potential health issues; (5) the privacy of the individual involved in the studies will be maintained per current protocols; and (6) research will be planned within normal ISS increment planning cycles.

Each of the five feasible use cases are described in the sections below.

3.1. Earth-independent medical operations analog

This use case will simulate nominal medical operations, such as the crew monitoring their health status, care, and nutrition needs, and will simulate contingency medical emergencies. The simulation should involve a minimum of two crewmembers (a simulated patient and care giver) for a duration of up to two days with starting communication delays of five minutes. To support this simulation, a medical workspace could be configured on the ISS, and astronauts should use relevant onboard health and performance data to make decisions.

Additionally, the crew might need more intensive medical training before flight, and be selected based on their medical knowledge, experience, and background. Finally, this simulation should be developed and tested on the ground before being conducted on the ISS. To support international coordination and planning, an international working group should be assigned to define the medical data that will be required by an autonomous crew, the support required to aid the crew in making decisions, and the training required for the crew, and the working group should develop a roadmap for these studies with a timeline that includes the ISS.

3.2. Earth-independent integrated operations analog

For this use case, a communication time delay will be implemented between the ISS and ground support personnel, possibly with a simulated exploration MCC. The communication time delay will begin with a maximum of five minutes over a period of two weeks. Shorter delays may be implemented initially, and the five minutes should be reassessed after the first simulation is complete based on the goals of both psychological study and emergency event simulation, which may need longer delays. Nominally, the simulation would include the entire ISS crew, although individuals may opt out of the research. To ensure the safety of the crew during this simulation, MCC would maintain control of the flight vehicle, and the crew would not close hatches between modules or block access to crew return vehicles.

To prepare for the simulation, the international partners should first identify operational concepts for the most relevant tasks and emergency procedures to be tested on board the ISS with the simulated exploration MCC (see section 2.9). Then, the ISS program should determine which scenarios and procedures are acceptable for simulations and define decision gates for when the duration of the simulation could be extended. Finally, the ISS program should develop simulations that can be implemented and tested on the ground before testing begins on the ISS. The ISS program should (1) assign a multi-lateral team who will develop an integrated approach to using the various Earth, ISS, and lunar platforms, (2) develop a testing strategy to migrate the simulations from ground-based testing to testing in space using a simulated exploration MCC to support the simulation, and (3) develop operations objectives, requirements, and plans.

3.3. Earth-independent ECLSS, food, and autonomy analog

This use case will extend studies in ground analogs of spaceflight to test the exploration food system and the ECLSS on the ISS over a one-year period. The crewmembers will conduct Earth-independent monitoring, decision making, maintenance, and repair procedures for the habitation systems components. Additionally, the use case will involve the entire ISS (all partner modules) and an exploration-class food system for the entire crew, although individuals may opt out of the research.

To prepare for this simulation on ISS, the ISS program will need final simulation parameters that are based on the study data obtained in the highest-fidelity ground analogs[2]. Also, the ISS partners should identify exploration systems (e.g. food, life support systems) and components (e.g. pre-packaged food and replacement parts) that are already developed and appropriate for studies in an ISS-based analog of Mars transit. The ISS partners should develop a multi-agency exploration food systems roadmap to guide development and validation of the food system that will be used for a Mars mission. This roadmap will help coordinate the inclusion of exploration systems and components from the different international partners. The ISS program should provide timely notice of the year this simulation will be implemented on the ISS so that ground analog studies can be completed and all agencies can align in their hardware development and testing approaches.

3.4. Lower body negative pressure (LBNP) countermeasure analog

This use case will implement an LBNP [48] for individual crewmembers as a countermeasure to the effects of exposure to microgravity. Data from active research on LBNP conducted by NASA and IBMP has not been shared broadly with international partners. The international partners have requested this data so they can assess the value of this countermeasure for mitigating the effects of long-duration exposure to microgravity and the effects of gravity transitions, and as a possible method of preventing SANS. To prepare for engaging more partners in this work on the ISS, the international partners should assess the outcomes of available LBNP ground and flight studies. The ISS program should assign an international working group to define, select, and exchange information on countermeasure methods and procedures to accelerate convergence on best practices as more information is obtained.

3.5. Postlanding surface fitness analog

This use case will assess how crews perform tasks shortly after they land on the Mars surface after a long transit in a microgravity environment. The task will be performed with monitored autonomy and using measures to mitigate the effects of microgravity on the sensorimotor system before, during, and after spaceflight. The crew could self-administer health and performance assessments and rehabilitation measures. Simulated tasks and operations will include egress, EVA, and manual control such as for telerobotics after return to gravity or to simulated Martian gravity. Consistent performance measures will be assessed one to 60 hours after landing in the Boeing, SpaceX, or Soyuz vehicles. Studies involving the NASA Commercial Crew Program must be planned so they do not impact the current operation timeline agreements zero to four hours after landing. Also, ground personnel could provide support to the crew without “breaking” the simulation. Finally, the entire crew must undergo testing of the simulated task around the same time after landing, although individual crewmembers may opt out of the research.

To prepare for this ISS-based simulation, researchers and planners must identify Mars-relevant tasks and countermeasures, and develop these new post-landing procedures in coordination with the ISS Program, the Commercial Crew Program, and the vehicle providers. The international partners should develop an integrated plan that balances research data collection needs and health monitoring activities after flight, with post-landing plans and data measures coordinated between the Russian and American landings. Additionally, they should develop an integrated ground and flight campaign to develop countermeasures for spaceflight-induced sensorimotor deficits that include (1) testing on-orbit training techniques and their efficacy for protecting the crew

---

[2] Examples of the current highest-fidelity ground analogs include the Human Research Analog (HERA), Crew Health and Performance Exploration Analogs (CHAPEA), Nazemnyy Eksperimental’nyy Kompleks (NEK), and:envihab.

after they land on a planetary surface, (2) testing crewmembers after landing to determine how to improve rehabilitation measures because performing tasks unaided on the Mars surface after a long transit in a microgravity environment will be more challenging than performing tasks with the assistance of ground personnel after a ISS mission, and (3) evaluating whether data gathered from crewmembers of shorter duration missions can be extrapolated to evaluate the effects of longer-duration missions, thus increasing the number of subjects who can be assessed. Ultimately, this use case will extend the knowledge gained from the "Field Test" studies of crewmembers' sensorimotor performance after Soyuz landings [39] to include new observations and tests of new countermeasures.

4. Perspectives of stakeholders

The workshop participants discussed a diversity of ISS-based Mars transit simulations that varied in duration, type, and purpose (section 2). It is possible that some of the use cases could be misunderstood as they move toward implementation, even if, as recommended in this report (section 3), a phased-in approach is implemented using shorter durations and moderate interventions first. During the final set of workshop sessions, the participants focused on concerns that might be associated with simulations of isolation and confinement and gravity transitions. Astronauts, flight operators (mission operations and test conductors), senior managers, and representatives of the user community provided their perspectives regarding the challenges of implementing these studies and identified possible opportunities. This activity raised several concerns regarding use of the ISS as an analog of Mars missions. Because ISS operations and use cases will be performed concurrently, the identified concerns have cross-scenario relevance. The five key concerns identified by the workshop participants are described below along with their suggestions to mitigate these concerns.

Concern 1—Safety of the crew. Maintaining the crews' safety during simulations of the isolation during a Mars mission is a major concern, and it will also be critical to protect the crew during the flight and the post-landing simulations. The crew should wear devices to monitor specific health parameters, such as heart rate, blood pressure, and calories burned. Protocols and ground rules for stopping the study should be in place. In addition, the crew should have one flight surgeon available to them in case of an emergency. The crew should be highly trained to deal with medical issues, as they would be during a trip to Mars. In the absence of direct flight surgeon support, the crew should be sufficiently fit to cope with landing and to perform surface activities on the first few days after landing.

Concern 2—Infrastructure and fidelity trade off. This concern is associated with knowing and verifying the level of fidelity of an ISS-based Mars simulation compared to an actual Mars activity. It is logistically challenging to isolate some of the crewmembers on the ISS (e.g. separate quarters, separate workload), and this type of isolation may not reflect the isolation conditions on a Mars mission. If some of the ISS crewmembers are separated from the others this could create issues over time because they don't have access to all the amenities of the ISS. Therefore, a separate module on the ISS may be required to conduct these isolation studies.

In addition, because the actions the crew will have to perform during an actual Mars mission are not yet established, simulations on the ISS may not match the final requirements. Also, details of what the crew will have to do on the Mars surface, such as while they exit the spacecraft and drive a crew vehicle, are still unknown. Thus simulated training and preparations for these activities may not have the correct fidelity. To counter some of the fidelity concerns, a core end-to-end simulation package will be needed. Well-defined experiments with the proper justification for the protocols will also be necessary. All the ISS partners should approve the protocol, and the crew must be completely informed and willing to participate in the simulation.

Concern 3—Social concerns. Because communication delays will be longer during a Mars mission than during an ISS mission, family members may find it more difficult to be isolated from the crewmembers, which will induce stress for the family as well as for the crewmember. Protocols should be established to treat anticipated psychological issues that arise from delayed-communication-induced isolation. In addition, increased emotional support should be provided to the families. Short tests can be used initially to evaluate whether the simulation helps develop support for both the crewmembers and their families in support of future Mars missions, and to improve subsequent simulation approaches.

Concern 4—How to keep the crew motivated? Keeping the crewmembers of simulated Mars missions motivated and busy doing real work that they know corresponds to activities that will occur during a real Mars mission will be challenging. The simulation planners must determine which Mars mission activities should be incorporated into the simulation. Thus, the simulation planners should coordinate their efforts with Mars mission operations planners.

Concern 5—Cost and time. The cost of simulation studies and whether these studies would interfere with NASA's strategic schedule for crewed missions to Mars is a concern. The scientific and operational return on investment must be understood to justify the cost of these simulations. However, it is paramount that simulations are conducted on the ISS because integrated exposure to all five spaceflight hazards during realistic mission operations cannot be simulated on the ground. In many cases, software and operations that are developed for an ISS-based Mars mission simulation will guide development of software and operations necessary for future Mars missions. Thus, cost and time spent on ISS4Mars simulations could also provide benefits and cost savings for future development.

5. Discussion and recommendations

The ISS international partnership recently celebrated 20 years of continuous operations. Those past 20 years of continued human presence on the ISS have set the stage for humankind's future in space. The ISS is now reaching its possibly last, but potentially golden, decade of use with increased crew time, increased capabilities, and upgraded infrastructure. During the next decade of operations, the ISS will continue to serve as the world's leading laboratory for cutting-edge research and technology development that will enable human and robotic exploration of the Moon and Mars, advancing critical capabilities that will take humans further into space and reducing the cost of human spaceflight.

It is critical that we learn from prior spaceflight experience and recognize the limits of that experience. A lot remains be to understood about the physiological and performance effects induced by exposure to spaceflight hazards such as radiation, altered gravity, and hostile environments, as well as about the unique challenges in providing medical support, human factors, and behavioral health support, which are all critical to successful human exploration of deep space.

Crews travelling to Mars must be more self-reliant than the crews of any other previous space mission, and spacecraft systems and operations will need to be more automated, efficient, and reliable to support the health and safety of these crews. The key technologies and processes that future crews of long-duration exploration mission will need to live in a harsh environment with no possibilities for resupply still need to be properly and systematically tested. The ISS is therefore a critical platform for obtaining this required knowledge. Using the ISS as a testbed for Moon and Mars operations will afford extrapolation and translation of knowledge to space exploration systems and will identify the technologies required for humans to explore deep space.

The participants of the ISS4Mars workshop suggested innovative ways of using the ISS as a testbed and research analog for future deep space exploration missions, and they identified a set of technically feasible use cases that enable sustainable, affordable, sound research that will help maintain crewmembers' health and performance during these challenging missions. The participants of the ISS4Mars workshop also identified some activities that have already begun that could be expanded into an integrated set of ISS activities that will fill the knowledge and capability gaps needed for exploration-class missions. Changing the way that research is conducted and technology is tested on the ISS will increase Mars mission readiness. Testing concepts of operations, training, crew interfaces, and logistics on the ISS will provide an opportunity to obtain operational knowledge in a relevant environment without the added costs and risk associated with integrating new technologies and advanced systems into a completely new operational system.

Implementing the use cases described in this report will require a change to the current approach for using the ISS and may impact current research, activities, and priorities of work conducted by all the ISS partners. For instance, the use cases will affect crew time, upmass, and downmass, which are already highly constrained, and the ISS partners must be willing to use some of those precious resources for the ISS4-Mars use case studies. Technical and structural feasibility of the use cases will have to be assessed. If feasibility is confirmed, the ISS program will have to adapt the current ISS planning, solve operational challenges, and ensure crew safety. The ISS operations team and the participating crewmembers must consider and accept the possibility of increased risks for crew error or inefficiencies during increased crew autonomy.

Finally, it will be challenging to adapt and shape the proposed ISS4-Mars use cases and incorporate them into the overall ISS research planning. To effectively implement ISS-based Mars simulation activities across the entire international partnership, the results and recommendations of the ISS4Mars workshops have been handed over to the ISS Multilateral Human Research Panel for Exploration (MHRPE). This group coordinates multilateral human biomedical research on the ISS, defines common rules and guidelines to achieve the common goals and objectives of ISS biomedical research across the partnership, and coordinates medical operations that apply to human research exploration. The MHRPE will work collaboratively to assess the ISS4Mars use cases and develop a set of clear scientific and operational objectives of added value to exploration missions. They will then define scenarios to execute the use cases, while working closely with the ISS program and other stakeholders (science and engineering, programs, mission operations, payload utilization management, transportation providers, crew, safety, etc.) to confirm feasibility on the ISS platform, and they will work with the ISS Program to resolve any concerns or conflicts with other ISS research and operational activities. The MHRPE will guide any required international research and technology developments that support ground-based work, identify specific experimental protocols that use specified standard operating procedures and measures or technologies, and will clarify data sharing plans.

It is understood that nothing can ever truly replicate the actual experience of a Mars mission, but mimicking as many different aspects of the trip as possible will help prepare for these missions. Admittedly, the risks crews will face during deep space travel are immense, but they are not impossible to overcome. The ISS has a highly successful record of operations that have paved the way for many new inventions and opportunities. The coordinators and participants in the ISS4Mars workshops hope that the ISS will have an even greater impact on space exploration by enabling travel beyond low Earth orbit.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This manuscript was the result of the participation and contributions of over 100 scientists, operations experts, and leaders from multiple international space agencies, including substantial contributions from a larger organizing committee and additional contributions, as outlined in Appendix A. Co-authors on this manuscript met weekly to monthly over two years to assure the success of the workshop; they contributed to developing this report by refining the discussions at the meeting into a feasible set of approaches captured in use cases, ground rules and assumptions; and they wrote or edited different sections of the manuscript. Waid and Robinson integrated the initial NASA-internal strategy between the NASA and ISS Programs. Waid, Robinson, and Scimemi coordinated the international organizing committee, 2020-2021 international workshops, and manuscript development. Waid developed and refined the use-case approach and wrote the first draft of the manuscript. Narici coordinated conference discussions, the first international meeting in 2019, coined the ISS4Mars name, and shaped the organizing committee. Marcil brought mediation approaches to the team that changed the overall meeting structure and dynamics. Ngo-Anh coordinated and enabled ESA leadership support that enabled innovative discussions by their member agencies. Siegel moderated breakout meetings and coordinated and edited the minutes of the meeting and breakout group discussions. Sato added considerations of life science integration beyond human performance, such as in life support, microbiome, and food, that broadened the discipline scope and engagement. Stang coordinated the manuscript with the journal editor. Dempsey, McPhee, and Johnson-Green coordinated the transition from meeting results to implementation planning and incorporated that perspective into their edits.

We want to thank our amazing advisor and facilitator, Sally Rideout (CSA) whose creative solutions made this workshop more effective than it would have been in person. We also thank Erin Welshans who helped us keep the work coordinated and flowing across so many sessions and numerous virtual meetings. Peter Gräf (DLR) first proposed the idea of an international workshop and offered to host it at :envihab in Germany, just months before the global pandemic was declared. Oleg Kotov (IBMP), Max Kharlamov (GCTC), Boris Shishkov (Roscosmos), and Vasily Savinkov (Roscosmos) provided important perspectives and opportunities for developing shared plans across the full international partnership. Didier Chaput and Alain Maillet provided similar coordination between the organizing committee and Le site du Centre national d'études spatiales (CNES). Key ISS leaders, including Vittorio Cotronei (ASI), Robyn Gatens (NASA), Joel Montalbano (NASA), Bill Paloski (NASA, retired), Sam Scimemi (NASA), and Isabelle Tremblay (CSA), helped to create a supportive space for new creative thinking about ISS use. Critical discussions with leaders from crew and flight operations, including Meghan Behnken (NASA), Satoshi Furukawa (JAXA), David Korth (NASA), Yuri Malenchenko (GCTC), and Royce Renfrew (NASA) were very influential, even as their flight responsibilities changed and they could not participate in this set of workshops. Michelle Rucker (NASA) provided a clear vision of updated Mars architectures and operations that transformed thinking about opportunities for relevant research on ISS. We also thank our Russian language interpreters, Natalie Campiono, Connie Lamb, Tatyana Menkin, for helping make the discussions flow so smoothly, and Kerry George, for reviewing and technical editing of the final revision for the manuscript.

Each ISS partner provided funding to support their respective representatives’ participation in ISS4Mars strategy development. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A.

This appendix includes the major participants and invitees and their primary perspective during the workshop discussions. This is provided to help illustrate the need for an international inter-agency focus (instead of a more typical meeting open to the full scientific community). The group still included scientific discipline experts from across agencies, and the multidisciplinary nature of the discussions to frame changes in operations of ISS and approaches to conducting new kinds of research were still grounded in technical and programmatic realism. The authors apologize for any inadvertent omissions of the perspectives and roles brought to this complex and long ranging set of virtual meetings. Not all invitees participated in every meeting across multiple conversations and breakout groups. Although many of the participants also had a variety of backgrounds in engineering, we did not track this as a separate perspective at this meeting given it is the predominant organizational culture at all space agencies.

Name	Agency*	Identified Perspective[†]	Special Role(s)[‡]
Abadie, Laurie	NASA	Manager	
Abeln, Vera	DLR Invited	Scientist	
Allen, John	NASA	Manager	
Augelli, Mauro	CNES Invited	Industry	
Auñon-Chancellor, Serena	NASA	Crew, Medicine	S
Baumann, David	NASA	Manager	
Beblo-Vranesevic, Kristina	DLR/ME	Scientist	S
Berger, Thomas	DLR/ME	Scientist	S
Bhattacharya, Sharmila	NASA	Scientist	
Bleacher, Jacob	NASA	Scientist	
Blouvac, Jean	CNES Invited	Scientist	
Boggs, Kathleen	NASA	Technologist, Manager	M
Braun, Markus	DLR	Scientist, Manager	
Buchli, Jennifer	NASA	Scientist	OC
Buckley, Nicole	ESA	Scientist, Manager	S
Canton, Remi	CNES		
Carnell, Lisa	NASA	Scientist	R
Caron, Mathieu	CSA		
Castagnolo, Dario	ASI Invited	Industry	S
Cotronei, Vittorio	ASI	Manager	
Chappell, Michael	NASA	Manager	
Choukèr, Alexander	DLR Invited	Scientist	S
Chaput, Didier	CNES	Manager	OC
Costello, Kirt	NASA	Scientist, Manager	S
Craig, Doug	NASA	Manager	
Davison, Stephen	NASA	Manager	
Denzer, Lisa	ESA		M
Dolgov, Pavel	GCTC	Operator	S
Douglas, Grace	NASA	Scientist	S
Drake, Bret	NASA	Manager	
Drescher, Jürgen	DLR/ME	Scientist, Manager	S
Ewald, Reinhold	DLR Invited, ESA	Crew	
Falker, Jay	NASA	Technologist	
Ferranti, Francesca	ASI		
Fogarty, Jennifer	NASA	Scientist	OC, S
Frank, Jeremy	NASA	Technologist	S
Frings-Meuthen, Petra	DLR/ME	Scientist	
Galinski, Thomas	DLR	Manager	S
Gatens, Robyn	NASA	Manager	S
Gauquelinkoch, Guillemette	CNES		
Gensler, Janejit	NASA	Manager	
Gil, Valerie	CSA		
Girgenrath, Michaela	DLR	Scientist, Manager	OC, S, WC
Graef, Peter	DLR	Scientist, Manager	OC
Green, Jim	NASA	Scientist, Manager	
Gunga, Hanns Christian	DLR Invited	Scientist	
Gushin, Vadim	IBMP	Medicine	S
Harada, Satoshi	JAXA		R
Hauslage, Jens	DLR/ME	Scientist	S
Hoffman, Stephen	NASA	Manager	
Inoue, Natsuhiko	JAXA		
Janoiko, Barbara	NASA	Operator	
Johnson-Green, Perry	CSA	Scientist, Manager	S, WC
Jordan, Jens	DLR/ME	Scientist, Manager	OC, S

Name	Agency*	Identified Perspective†	Special Role(s)‡
Judd, Emily	NASA	Manager	
Kharlamov, Maxim	GCTC	Operator, Manager	S
Kminek, Gerhard	ESA	Scientist	S
Kotov, Oleg	IBMP	Crew, Manager	OC, S
Kundrot, Craig	NASA	Scientist, Manager	
Kuritsyn, Andrey	GCTC	Operator	OC
Kuyumjian, Raffi	CSA	Medicine	OC, S
Lasseur, Christophe	ESA	Scientist	S
Laurie, Steven	NASA	Medicine	S
Lehnhardt, Kris	NASA	Scientist, Medicine	S
Lloyd, Charles	NASA	Manager	
Lobascio, Cesare	ASI Invited	Industry	S
Macias, Brandon	NASA	Scientist	S
Maillet, Alain	CNES		OC
Marcil, Isabelle	CSA	Scientist	OC, R, WC
Mari, Sylvia	ASI		
Maples, Whitney	NASA	Operator	S
Mascetti, Gabriele	ASI	Manager	S
Matsuda, Chie	JAXA		S
McCullough, Lucia	NASA	Manager	
McPhee, Jancy	NASA	Scientist, Manager	R, WC
Möller, Ralf	DLR/ME	Scientist	S
Montalbano, Joel	NASA	Manager	S
Mühl, Christian	DLR/ME	Scientist	S
Mulder, Edwin	DLR/ME	Scientist	
Murakami, Kejii	JAXA	Manager	OC
Nakanoya, Sogo	JAXA		S
Narici, Livio	ASI	Scientist	OC, S, WC
Neumann, Benjy	NASA	Manager	
Ngo-Anh, Jennifer	ESA	Medicine, Manager	OC, S, WC
Orlov, Oleg	IBMP	Scientist, Manager	S
Paille, Christel	ESA		S
Paloski, Bill	NASA	Manager	S
Parks, Andy	NASA	International Relations	
Pecena, Yvonne	DLR/ME	Scientist	
Picano, Jim	NASA	Medicine	S
Piechowski, Sarah	DLR/ME	Scientist	S
Platts, Steven	NASA	Scientist, Manager	
Rayl, Nicole	NASA	Manager	
Reagan, Marcum	NASA	Operator	
Regburg, Aaron	NASA	Scientist	S
Rettberg, Petra	DLR/ME	Scientist	S
Rideout, Sally	CSA	Policy Analyst	F
Rittweger, Jörn	DLR/ME	Scientist	OC, R, S
Robinson, Julie	NASA	Scientist, Manager	OC, S, WC
Rogon, Christian	DLR	Scientist, Manager	
Rosenberg, Marissa	NASA	Scientist	S
Rucker, Michelle	NASA	Manager	S
Ruttley, Tara	NASA	Scientist	M
Saint-Jacques, David	CSA	Crew, Medicine	S
Salnikov, Alexey	IBMP	Scientist	S
Sato, Kevin	NASA	Scientist	OC, S, WC
Savinkov, Vasily	Roscomos	Manager	S
Schmitt, Didier	ESA	Manager	S
Schneider, Stefan	DLR Invited	Scientist	S
Schneider, Victor	NASA	Medicine	
Schön, Andreas	ESA	Manager	
Scimemi, Sam	NASA	Manager	OC, S
Seine, Rüdiger	ESA		S
Shirakawa, Masaki	JAXA	Manager	S
Shishkov, Boris	Roscosmos	Manager	S
Siegel, Bette	NASA	Scientist	R, WC
Spry, Andy	NASA	Scientist	
Stahn, Alexander	DLR Invited	Scientist	
Stang, Katrin	DLR	Scientist, Manager	OC, S, WC
Stern, Claudia	DLR/ME	Scientist	
Suresh, Rahul	NASA	Medicine	
Tank, Jens	DLR/ME	Scientist	S
Thompson, Moriah	NASA	Medicine	S
Totoki, Machiko	JAXA		R
Tremblay, Isabelle	CSA	Manager	OC, S
Umeura, Sayaka	JAXA		M
Van Ombergen, Angelique	ESA		R, S
Vessey, Brandon	NASA	Scientist	S

Name	Agency*	Identified Perspective†	Special Role(s)‡
Waid, Michael	NASA	Manager	OC, R, S, WC
Wallace, Sarah	NASA	Scientist	S
Watkins, Sharmi	NASA	Medicine	S
Weerts, Guillaume	ESA		S
Whitmire, Sandra	NASA	Scientist	S
Williams, Thomas	NASA	Scientist	S
Yamamoto, Masafumi	JAXA		

*Agencies: Italian Space Agency (ASI), Canadian Space Agency (CSA), National Center for Space Studies/Institute for Space Medicine and Physiology (CNES/MEDES), German Aerospace Center (DLR), European Space Agency (ESA), Institute of Biomedical Problems (IBMP), Japan Aerospace Exploration Agency (JAXA), and National Aeronautics and Space Administration (NASA).

†Perspectives noted: Crew (astronauts and cosmonauts), Industry, International Relations, Manager (including engineering program management), Medicine (including medical doctors and flight medicine specialties), Operator (including training and mission operations specialties), Policy Analyst, Scientist, and Technologist.

‡Special roles are: OC = Organizing Committee, M = Moderator, S = Speaker, R = Rapporteur, F = Facilitator, WC = Writing Committee.

References

[1] Robinson J.A, Costello K.A, Brady D.D. International Space Station Benefits for Humanity. 3rd ed. Houston: NASA; 2018.

[2] Charles JB, Arya M, Kundrot CE. Use of International Space Station to simulate interplanetary transit: Human health and performance applicability of current increment durations and extended durations. NASA Technical Memorandum; 2011. Report No.:NASA/TM–2011-216143.

[3] Linck E, Crane KW, Zuckerman BL, Corbin BA, Myers, RM, Williams SR, et al. Science and Technology Policy Institute. Evaluation of a human mission to Mars by 2033. Science and Technology Policy Institute: Washington, DC; 2019.

[4] Charles JB, Pietrzyk RA. A year on the International Space Station: implementing a long-duration biomedical research mission. Aerosp Med Hum Perform 2019;90:4–11. https://doi: 10.3357/AMHP.5178.2019.

[5] Robinson J, Waid MC, Korth D, Rucker M, Renfrew R. Innovative approaches to using the International Space Station as a Mars transit analog. In proceedings of the 70th International Astronautical Congress; 2019 October 21-25; Washington, DC. IAC-19.B.3.3.142019.

[6] Robinson JA, Scimemi S, Waid MC, Fogarty J, Paloski WH, Rucker M, et al. Preparing for human missions to Mars: The role of ISS and Artemis as analogs for research and technology testing. In proceedings of the 71st International Astronautical Congress; 2020 October 12-14; Washington, DC. IAC-20.B3.3.12.

[7] Reitz G, Narici L. The ISS as a platform for a fully simulated Mars voyage. In the proceedings of 2nd COSPAR Scientific Assembly; 2018 July 14-22; Pasadena, California. Abstract id. PEX.2-15-18.

[8] Narici L, Reitz G. Integrated simulations of Mars flights on the ISS. In the proceeding of the 68th International Astronautical Conference; 2017 September 25-29; Adelaide, Australia. IAC-17-A1.4.2.

[9] Narici L, Reitz G, Lobascio C. Integrated simulations of Mars flights on the ISS. Adv Space Res 2018;62:990–6. https://doi.org/10.1016/j.asr.2018.06.020.

[10] Morgan E. Utilizing the International Space Station as a simulation platform for deep space travel. In the proceeding of the 68th International Astronautical Conference; 2017 September 25-29; Adelaide, Australia. IAC-17.A1.4.3.

[11] Löbrich M, Jeggo P.A. Hazards of human spaceflight. Science 2019;364(6436): 127–8.

[12] Abadie LJ, Lloyd CW, Shelhamer MJ. The human body in space. 2018.

[13] Sibonga J, Matsumoto T, Jones J, Shapiro J, Lang T, Shackelford L, et al. Resistive exercise in astronauts on prolonged spaceflights provides partial protection against spaceflight-induced bone loss. Bone 2019;128:112037.

[14] Bruce R.J, Ott C.M, Skuratov V.M, Pierson D.L. Microbial surveillance of potable water sources of the International Space Station. J Aerosp 2005;114:283–92.

[15] Shelhamer M. Trends in sensorimotor research and countermeasures for exploration-class space flights. Front Syst Neurosci 2015;9:115. https://doi: 10.3389/fnsys.2015.00115.

[16] Stenger MB, Tarver WJ. Evidence report: Risk of spaceflight associated neuro-ocular syndrome (SANS). NASA Human Research Program: Houston; 2017.

[17] Hughson R.L, Shoemaker J.K, Blaber A.P, Arbeille P, Greaves D.K, Pereira-Junior P.P, et al. Cardiovascular regulation during long-duration spaceflights to the International Space Station. J Appl Physiol 2012;10.1152/japplphysiol.01196.2011(112):719–27.

[18] Chancellor J.C, Blue R.S, Cengel K.A, Auñón-Chancellor S.M, Rubins K.H, Katzgraber H.G, et al. Limitations in predicting the space radiation health risk for exploration astronauts. npj Microgravity 2018;4:8. https://doi.org/10.1038/s41526-018-0043-2.

[19] Durante M, Cucinotta F.A. Heavy ion carcinogenesis and human space exploration. Nat Rev Cancer 2008;8:465–72. https://doi.org/10.1038/nrc2391. https://10.1038/nrc2391.

[20] Meerman M, Bracco Gartner TCL, Buikema JW, Wu SM, Siddiq S, Bouten CVC, et al. Myocardial disease and long-distance space travel: Solving the radiation problem. Front Cardiovasc Med 2021;8;631985. https://doi: 10.3389/fcvm.2021.631985.

[21] Cucinotta F.A, Alp M, Sulzman F.M, Wang M. Space radiation risks to the central nervous system. Life Sci Space Res 2014;2:54–69.

[22] Parihar V.K, Allen B, Tran K.K, Macaraeg T.G, Chu E.M, Kwok S.F, et al. What happens to your brain on the way to Mars. Sci Adv 2015;1(4).

[23] R. Jandial R. Hoshide J.D. Waters C.L. Limoli Space-brain: the negative effects of space exposure on the central nervous system Surg Neurol Int 9 2018 9 https://doi: 10.4103/sni.sni_250_17.

[24] Lumniczky K, Candéias SM, Gaipl US, Frey B. Editorial: Radiation and the Immune system: Current knowledge and future perspectives. Front Immunol 2018; 8:1933. https://doi: 10.3389/fimmu.2017.01933.

[25] Ray K, Choudhuri R. Effects of radiation on the reproductive system. In: Gupta R.C, editor. Reproductive and developmental toxicology. Academic Press; 2011. p. 291–329.

[26] Davis J.R, Johnson R, Stepanek J, Fogarty J.A. Fundamentals of Aerospace Medicine. 4th ed. Philadelphia: Lippincott, Williams and Wilkins; 2008.

[27] Cooper M, Douglas G, Perchonok M. Developing the NASA food system for long-duration missions. J Food Sci 2011;76:40–8. https://doi: 10.1111/j.1750-3841.2010.01982.x.

[28] Douglas GL, Zwart SR, Smith SM. Space food for thought: Challenges and considerations for food and nutrition on Exploration missions. J Nutrition 2020; 150;2242-44. https://doi: 10.1093/jn/nxaa188.

[29] Landon LB, Slack KJ, Barrett JD. Teamwork and collaboration in long-duration space missions: Going to extremes. Am Psychol 2018;73:563–75, 2018. https://doi: 10.1093/jn/nxaa188.

[30] Pagel J, Choukèr A. Effects of isolation and confinement on humans-implications for manned space explorations. J Appl Physiol 2016;10.1152/japplphysiol.00928.2015(15):1449–57.

[31] Smith M, Bleacher J, Craig D, Cremins T, Mahoney E, Robinson JA, et al. NASA's path from low-earth orbit to the moon and on to Mars. In proceedings of the 71st International Astronautical Congress; 2020 October 12-14; Washington, DC. IAC-20.A3.1.1.

[32] Reagan ML, Janoiko BA, Parker ML, Johnson JE, Chappell SP, Abercromby AF. NASA's Analog Missions: Driving Exploration Through Innovative Testing. In the proceedings of the AIAA SPACE 2012 Conference & Exposition; 2012 September 12-13; Pasadena, California. AIAA 2012-5238.

[33] Olson J. Voyages: charting the course for sustainable human space exploration. NASA Hampton, Virginia; NASA report; 2011. Report No.: NP-2011-06-395-LaRC.

[34] Nasrini J, Hermosillo E, Dinges D, Moore T.M, Gur R.C, Basner M. Cognitive performance during confinement and sleep restriction in NASA's Human Exploration Research Analog (HERA). Front Physiol 2020;11:394. https://doi.org/10.3389/fphys.2020.00394.

[35] Möstl S, Orter S, Hoffmann F, Bachler M, Hametner B, Wassertheurer S, et al. Limited effect of 60-days strict head down tilt bed rest on vascular aging. Front Physiol 2021;12:685473.

[36] Morabito D, Hastrup R. Communicating with Mars during periods of solar conjunction. In the proceedings of the EEE Aerospace Conference; 2002 March 5-12; Big Sky, Montana. p. 4.1306.

[37] Frank J, McGuire K, Moses H, Stephenson J. Developing decision aids to enable human spaceflight autonomy. AI Magazine 2017;37:46–54. https://doi.org/10.1609/aimag.v37i4.2683.

[38] Robinson J.A., Waid M., Ngo-anh, T.J., Marcil, I., Shishkov, B., Murakami, K., Stang, K., Kotov, O., Cotronei, V., Narici, L., Savinkov, V., Girgenrath, M., Johnson-Green, P., Siegel, B., Sato, K., Scimeni, S., Gatens, R. Novel ways to use the International Space Station as an exploration analog: international progress in planning "ISS4Mars". In the proceedings of the 72nd International Astronautical Congress; 2021 October 25-29; Dubai, UAE. IAC-21.B3.3.2.

[39] Reschke M, Kozlovskaya IB, Kofman IS, Tomilovskaya SE, Cerisano JM, Bloomberg JJ, et al. Sensorimotor results from the joint NASA and Russian pilot field test. In the proceedings of the 2016 NASA Human Research Program Investigators Workshop; 2016 February 8-11; Galveston, TX.

[40] Gatens R, Anderson M. Evolution of the International Space Station life support and habitation systems for deep space exploration. In the proceeding of the 68th

International Astronautical Conference; 2017 September 25-29; Adelaide, Australia.

[41] Stetson HK, Haddock AT, Frank J, Cornelius R, Wang L, Garner L. AMO EXPRESS: A Command and Control Experiment for Crew Autonomy Onboard the International Space Station,“ in AIAA Space and Astronautics Forum and Exposition (AIAA SPACE 2015), Pasadena, CA, 2015.

[42] NASA. Decision Memorandum DM-1004: Planning Guidance for Artemis Mission Durations as Testbeds to Reduce Risks for Human Missions to Mars. NASA: Washington, DC, 2021.

[43] NASA. Decision Memorandum DM-1002: Mars Mission Duration Guidance for Human Risk Assessment and Research Planning Purposes. NASA: Washington, DC, 2020.

[44] National Research Council, Division on Engineering and Physical Sciences, Aeronautics and Space Engineering Board, Space Studies Board, Committee for the Decadal Survey on Biological and Physical Sciences in Space. Recapturing a future for space exploration: life and physical sciences research for a new era. Washington, DC: National Academy of Sciences Press; 2011. https://doi.org/10.17226/13048.

[45] Ching M, Gill TR, Moore C, Clawson JM, Cross A, Kessler PD, et al. NextSTEP Habitat Risk Reduction for Gateway. In proceedings of the 70th International Astronautical Congress; 2019 October 21-25; Washington, DC.

[46] Cromwell R.L, Scott J.M, Downs M, Yarbough P.O, Zanello S.B, Ploutz-Snyder L. Overview of the NASA 70-day bed rest study. Med Sci Sports Exerc 2018;10.1249/MSS.0000000000001617(50):1009–19.

[47] Garrett-Bakelman F.E, Darshi M, Green S.J, Gur R.C, Lin L, Macias B.R, et al. The NASA twins study: A multidimensional analysis of a year-long human spaceflight. Science 2019;364(6436).

[48] Goswami N, Blaber A, Hinghofer-Szalkay H, Convertino V. Lower body negative pressure: Physiological effects, applications, and implementation. Physiol Rev 2019;99:807–51. https://doi: 10.1152/physrev.00006.2018.

[49] Lobascio C, Bandini F, Gargioli E, Cardano M, Saia D. ISS4Mars: Employing ISS Modules for a Mars Mission Dry Run.In the proceeding of the 68th International Astronautical Conference; 2017 September 25-29; Adelaide, Australia International Astronautical Congress, Adelaide, 2017. IAC-17.A1.4.4.

[50] Menon A.S, Moynihan S, Garcia K, Sargsyan A. How NASA uses telemedicine to care for astronauts in space. Harvard Business Review 2017.

[51] Smitherman D, Schnell A. Gateway Lunar Habitat Modules as the Basis for a Modular Mars Transit Habitat. In the proceedings of the 2020 IEEE Aerospace Conference; 2020 March 7-14; Big Sky Montana.

[52] La Tessa C, Sivertz M, Chiang IH, Lowenstein D, Rusek A. Overview of the NASA space radiation laboratory. Life Sci Space Res (Amst.) 2016;11:18-23. https://doi:10.1016/j.lssr.2016.10.002.

[53] Calle C.I. The electrostatic environments of Mars and the Moon. J Physics Conf Series 2001;301:012006.

[54] J. Isobe et al. Carbon dioxide removal technologies for U.S. space vehicles: past, present, and future ICES-2016-425. 46th International Conference on Environmental Systems 2016.

[55] Gatens RL, et al., National Aeronautics and Space Administration environmental control and life support technology development and maturation for exploration, ICES-2015-111, 45th International Conference on Environmental Systems, 2015.

[56] Norcross J, Effects of the 8 psia/32% O_2 atmosphere on the human in the spaceflight environment. NASA/TM-2013-217377.

[57] Yang J, et al. Microbiology of the built environment in spacecraft used for human flight. Methods in Microbiology 2018;45:3–26.