IAC-25-A1,9,2,X96721

ISS4Mars: Using Low Earth Orbit Stations to Enable Human Exploration of Mars

Jancy McPhee[a]*, Livio Narici

[a] *The Aerospace Corporation, 2525 Bay Area Blvd, Houston, TX 77058 USA*
[b] *University of Rome Tor Vergata, INFN Tor Vergata, ASI, Rome, Italy Department of Aerospace Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario, Canada M5B 2K3*
* Corresponding Author

Abstract

ISS4Mars is a global initiative to use the International Space Station (ISS) as an analog of human missions to Mars. The ISS provides a spaceflight platform that can be used to test different operational scenarios that mimic the autonomy, duration, and communication delays expected during a Mars mission. Studies conducted on the ISS can assess the risks that astronauts will encounter during a Mars mission and the integrated technologies and countermeasures required to keep them safe. The idea of using the ISS as a testbed for a Mars Mission was first presented in Prague at the Humans in Space Symposium in 2015. After two international workshops, one held in Rome in 2018, and one held remotely in 2020–2021, space agencies agreed to implement a stepwise approach, starting with simple use cases. Five use cases were identified, and the international Multilateral Human Research Panel for Exploration (MHRPE) added more details to the use cases, including considerations for operational feasibility, and each agency's desired role in preparing for potential implementation. The MHRPE then selected four of these use cases and one space agency to lead the development of each implementation plan. These four use cases are described in this paper, focusing on which facets of a Mars mission they will survey and the operational challenges of implementing them on the ISS. The following practices regarding the ISS4Mars initiative are discussed: (1) scenarios, technologies, and countermeasures must be first tested in terrestrial analogs of spaceflight, parabolic flight, or suborbital and shorter duration orbital spaceflight; (2) ISS4Mars studies should not affect other research being conducted on the ISS, however, they should represent some of the highest priority research to enable human exploration; (3) commercial low Earth orbit (LEO) stations should be considered for implementing these studies post-ISS; (4) new international collaborative methods and partnerships should be pursued, if needed, to implement these studies on the ISS. These use cases are a first step toward using LEO and lunar platforms as analogs to prepare for future Mars missions. Ultimately, many, if not all, Mars mission operations will be tested in advance to optimize integration and synergy. This testing will require extensive planning, potentially involving scaling up single use cases to a multiple use case approach. By safely working close to Earth using the ISS4Mars approach, international agencies and commercial partners can develop the vehicles and tools needed to enable human exploration of Mars.
Keywords: International Space Station; low Earth orbit; human space exploration; Mars mission; human health; ISS4Mars

Acronyms/Abbreviations

ADAMS	Advanced Astronaut Medical Support
ARGOS	Active Response Gravity Offload System
CSA	Canadian Space Agency
CHAPEA	Crew Health and Performance Exploration Analog
ECLSS	Environmental Control and Life Support System
ESA	European Space Agency
IAC	International Astronautical Conference
ISS	International Space Station
LEO	Low Earth orbit
LBNP	Lower Body Negative Pressure
MHRPE	Multilateral Human Research Panel for Exploration
NASA	National Aeronautics and Space Administration
OI	Orthostatic Intolerance
SPEs	Solar Particle Events
SANS	Spaceflight Associated Neuro-ocular Syndrome
SG	Splinter Group

1. Introduction

Humanity is poised to explore further into the solar system, not just with robots, but in person. Many space agencies, academic institutions, and commercial entities worldwide share an interest in exploring Mars by the middle of this century. A mission to Mars will be unlike previous human experience of living and working in Low Earth Orbit (LEO) or past and near-term planned future lunar missions. Mars is much further away. During a mission to Mars, the crew will be exposed to spaceflight conditions for a much longer duration, and they will be required to operate much more autonomously.

A human mission to Mars is ambitious, and success is more likely if those interested in the endeavor partner together to develop and implement strategies that will reduce risk to the crew and boost overall readiness for the mission. Humans have been working in space for many decades, but many unknowns exist regarding how crewmembers will fare on a Mars mission, and these unknowns must be evaluated and mitigated. Terrestrial analogs of spaceflight conditions are very useful for preliminary evaluations, but a higher fidelity space analog would be best for later testing. About 10 years ago, a group of international colleagues reviewed whether the International Space Station (ISS) could be used as a Mars analog, and this discussion led to the formation of the ISS4Mars initiative. This paper will capture the original plans, status, and lessons learned.

2. Development of the Initial ISS4Mars Concept

ISS4Mars is currently a global initiative to use the ISS, and potentially future available LEO platforms, as an analog of human missions to Mars. The ISS4Mars idea was first presented at the Humans in Space Symposium in Prague, 2015 [1]. The initiative was described as using the ISS for a full, integrated test of operational procedures that will enable a human mission to Mars: the ISS, or part of it, would be used by the crew for a duration equal to that of the actual Mars mission to mimic mission operations. The ISS offers the best currently available spaceflight platform to test different operational scenarios and our level of readiness for Mars missions. Crew autonomy, mission duration, communication delays, microgravity, confinement, distance from Earth, and even the type and exposure level of radiation expected during a Mars mission are either already part of the ISS environment or could be simulated to a sufficiently high degree of fidelity, certainly higher than in ground-based analogs of spaceflight.

The proposal to use the ISS as a testbed was also supported by the notion that most research activities on the ISS could be classified into two categories: research in space (i.e., research that requires conditions such as microgravity but is not directly related to enabling human space exploration); and research for space (i.e., research necessary to enable human exploration). This latter category of research would culminate as a full-scale ISS4Mars assessment of all procedures and countermeasures derived from individual studies of this type (see Figure 1), see also [2].

Although the proposal was considered appealing, it immediately raised several significant concerns. The idea of allocating dedicated ISS resources (crew time, volume, etc.) for such tests called attention to the fundamental issue that the ISS was not originally designed for a large, integrated exploration mission simulation. Furthermore, many researchers were concerned that important ongoing or planned ISS experiments might be disrupted or even cancelled to enable an integrated ISS4Mars-like test. Additionally, the ISS4Mars approach required consensus among all ISS partners regarding priorities. Notably, an idea like the ISS4Mars initiative had been proposed even earlier [3], but was soon abandoned, possibly due to the complexity of inserting an integrated mission among already planned individual research studies on the ISS.

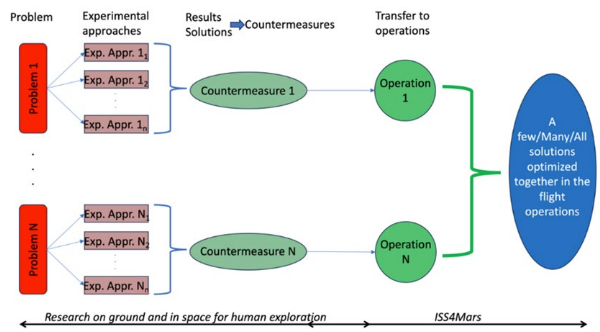

Fig 1. A simplified flow chart of the research required to enable human space exploration using an ISS4Mars approach. Once risk-problems (1 to N) are identified, multiple stand-alone studies could be conducted to propose countermeasures that may mitigate risk. The individual countermeasures would be implemented together to assess synergy and optimization and to measure current readiness for a Mars mission. The line on the bottom of the figure is a rough division between the single focused research studies (left side) and an integrated ISS4Mars test (right side) as originally proposed.

3. International workshops and transition to the International Multilateral Human Research Panel for Exploration (MHRPE)

Interested parties engaged in subsequent discussions during international meetings. A dedicated session was held at the 2017 International Astronautical Conference (IAC) in Adelaide (*Session A1.4: The International Space Station in LEO and the Deep Space Habitat in Cislunar Space as Platforms for Simulated Mars Voyages*). Delegates from all space agencies participated in the first international workshop fully focused on ISS4Mars, which was held in Rome in 2018 and paved the way for the creation of an ad hoc, agency-based ISS4Mars International Organizing Committee to further develop the top-level initiative and to plan a second international workshop. Further discussion took place in a panel at the 2019 IAC in Washington (*ISS-*

Moon-Mars: Using Spaceflight Platforms to Study and Simulate Future Missions, see also [4]), which also contributed to the design of this second international workshop. Initially planned to be held in Köln, the workshop instead became a year-long (2020–2021) series of remote meetings due to the pandemic. The workshop produced a final proposal for an initial, scaled-down, stepwise implementation of the ISS4Mars initiative that was designed as a more feasible first phase rather than the larger, fully integrated original concept [5,6]. The committee identified five use cases to implement on the ISS: *Earth-independent Medical Operations Use Case; Earth-independent Integrated Operations Use Case; Post-landing Surface Fitness Use Case; Earth-independent Environmental Control and Life Support System (ECLSS)/Food/Autonomy Use Case*; and *Lower-body Negative Pressure Countermeasure Use Case*. The intent was to implement this stepwise ISS4Mars approach before the planned end of life of the ISS. Later, partners could apply the ISS4Mars integrated operational concept on the ISS if time permitted, or on other platforms, including commercial LEO stations and possibly lunar-orbiting spacecraft.

The participants of the second international workshop then transitioned the descriptions of the top-level ISS4Mars use cases to the ISS-associated MHRPE. The MHRPE was asked to add more details to the use cases, including considerations for operational feasibility, and each agency's desired role in preparing protocols for executing operations on the ISS. The MHRPE selected four of these use cases. The fifth Mars analog use case (*Earth-independent Integrated Operations*) was not formally selected as a separate scenario because Mars mission autonomous operations would be naturally embedded into all the other studies. The MHRPE held several general virtual and face-to-face meetings with splinter groups (SG) of subject matter experts to design detailed candidate use case scenarios, and to address and extensively discuss several key items, including the following:

- A study that addresses a single Mars risk should lead to the definition of countermeasures to minimize that risk. When possible, countermeasures should first be tested extensively in terrestrial analogs, parabolic flights, or suborbital and shorter duration orbital spaceflights to prepare for optimal operations on the ISS. In this manner, the final tests would ideally be conducted on LEO stations, and ultimately these sites would be used to test synergies and to optimize operations of the integrated countermeasures to mitigate the greatest risks during a human mission to Mars.
- ISS4Mars studies should not interfere with the 'research in space' being conducted on the ISS (i.e., studies that require space conditions, such as microgravity). However, 'research for space' activities, such as the use cases and integrated ISS4Mars assessments, should be given the highest priority for testing because these studies enable human exploration overall, rather than addressing only a single relevant issue or risk.
- Future cislunar space platforms may have a higher fidelity for some of the anticipated Mars exploration stressors; however, these stations will be more distant from Earth, smaller, and will be more expensive and difficult to use. Thus, these synergistic studies should ideally be implemented on the ISS.
- Interested collaborators could potentially apply the same ISS4Mars concept on upcoming commercial LEO stations, employing a "LEO4Mars" evolution, ideally as integrated, high-fidelity studies of the countermeasures identified. As implied above, LEO stations enable Mars simulations that are relatively near to Earth, closer than cislunar platforms.
- New international collaborations and partnerships may be required to implement these studies on the ISS and on future LEO platforms.

Each agency reviewed the four detailed SG use case scenarios and indicated its desired role in the implementation of the use case. One (or two in some cases) space agency(ies) volunteered to lead the final study proposal development and operational implementation plans for each scenario on the ISS. Lead agencies planned to engage the international partners in participation and inform them via quarterly MHRPE meetings. The realization of the four use cases would represent a successful evolution of this initiative from concept to partial reality. Further work was anticipated to execute the more demanding, integrated ISS4Mars assessments on the ISS, or as eventually seemed more likely, on new platforms as a LEO4Mars concept.

The four use cases selected and further developed by MHRPE focused on surveying the risks of a Mars mission and the operational challenges of implementing them on the ISS. Below are descriptions of each use case as written by the MHRPE SGs, the challenges arising from the realities of implementing these studies on the ISS, and the drift in scope from the initial ISS4Mars conceptual ideals. As articulated below and in the concluding remarks, experts are gathering lessons learned to facilitate future studies on analogs of Mars missions.

4. Description of the Four Use Case Scenarios and Current Implementation

All the selected use cases shared a few key aspects of a Mars mission. The crew will be much more autonomous on a mission to Mars than they are on the

ISS. The time delay for communication from Mars to Earth (and vice versa) depends on the relative positions of the two planets and can vary from 3 to 24 minutes one way. This delay results in a greater need for the crew to make decisions and operate in transit and on the martian surface without the aid of ground support. SGs considered these common parameters when crafting more detailed ISS4Mars use case scenarios. Currently, the lead space agency(ies) are also addressing these factors as they craft implementation plans for assessing lower body negative pressure (LBNP), post-flight assessment, Earth-independent medical operations, and a food system (a simplified version of the original ECLSS/Food/Autonomy Use Case; details below).

4.1 LBNP Use Case

LBNP devices are specialized equipment designed to modulate human cardiovascular physiological responses by simulating the effects of standing upright in a gravitational field. The devices work by creating a vacuum around the lower body, trapping fluids below the waist and away from the central circulation (at heart level). LBNP has historically been used during spaceflight to reverse the headward fluid shift associated with gravitational unloading, particularly as a countermeasure for spaceflight-induced orthostatic intolerance (OI), i.e., difficulty adjusting blood pressure and heart rate when standing. If used with straps over the shoulders, this vacuum device could also provide musculoskeletal loading of the legs and spine when the body is pulled into the vacuum suit. The original ISS4Mars International Organizing Committee's concept for an LBNP Use Case was to assess the device as a countermeasure to prevent spaceflight associated neuro-ocular syndrome (SANS). SANS is characterized by changes in the structure of the eye and brain, for example, optic disc edema, choroidal-retinal folds, globe flattening, and ventricular enlargement. The functional impacts of SANS on crew health and performance are currently being studied.

This use case evolved in the hands of the experts on the MHRPE SG. The SG carefully reviewed data from international ground and spaceflight studies and matured the use case to evaluate LBNP as a countermeasure for OI and cardiovascular deconditioning in preparation for landing on Mars and end-of-mission return to Earth, but not to prevent SANS. The concept was to leverage the operational experience of Russian investigators using a tethered onboard LBNP suit ("Chibis") to prepare their ISS crew for return to Earth. The hypothesis was to apply LBNP training two weeks prior to descent to the martian surface or landing on Earth to mitigate hemodynamic responses suggestive of spaceflight-induced OI and cardiovascular deconditioning. The SG's decision to focus on LBNP as a cardiovascular countermeasure instead of a SANS countermeasure was influenced by multiple factors. First, the Russian cosmonauts were successfully using Chibis towards the end of a mission as a cardiovascular conditioning protocol, which coupled with fluid loading and wearing compression garments just before landing, seemed to protect against OI. Also, the SG decided that wearing an LBNP suit for 6 hours or more daily throughout the mission, as required to *prevent* SANS, would not be operationally feasible and would interfere with the other planned inflight science objectives. If the opportunity arose to expand the inflight use of LBNP as a SANS *treatment*, however, they would take advantage of this option.

After the SG developed its LBNP Use Case scenario, the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) offered to be co-leads to further define how to implement the LBNP Use Case on the ISS. The two agencies opted to share the leadership because both had invested in past mobile LBNP units, and ESA was actively advancing their suit design. In the agencies' hands, the LBNP scenario now focused on the suit as a potential multi-system countermeasure that included beneficial effects for OI, the musculoskeletal and proprioceptive systems, and early treatment of SANS. As mentioned earlier, team members reasoned that if LBNP was already on board a Mars mission for use as a cardiovascular fitness countermeasure, then it might prove useful to support crewmembers who show early signs of SANS, even if not worn daily by all crewmembers. The initial biggest technology concern regarding the LBNP suit was the need to develop an automated medical monitoring and shut-down system, thus not relying on the user to manually sense and shut down the LBNP vacuum to avoid syncope (fainting). Both agencies collaborated on evaluating technologies that could fill this role.

Due to new results and opportunities, the lead agencies are considering whether to continue LBNP as an ISS4Mars use case. Data from a head down tilt bedrest study suggests that LBNP effectively reduces headward fluid shift but does not prevent SANS-related optic disc edema (back of eye swelling) [7,8]. More studies in parabolic flight may be needed to determine whether bedrest is simply not a good analog of spaceflight-induced SANS, but current data provides no evidence that LBNP can mitigate SANS. Other realistic concerns regarding the use of LBNP as an ISS4Mars countermeasure include whether the crew will find the LBNP system palatable enough to use frequently during flight: Chibis was not designed for exploration use or for daily use during spaceflight. Any future LBNP device would additionally need to be tailored to focus more on mobility, comfort, and safety. NASA and ESA are thus discussing whether other tools, such as venous thigh cuffs, may be more effective and easier to employ as an in-flight countermeasure for a Mars mission.

4.2 Post-landing Assessment Use Case

Transitions from one gravity level to another can disrupt a crewmember's sensorimotor system, leading to space motion sickness, or symptoms of space adaptation syndrome, such as nausea, vomiting, and dizziness. These effects occur when transitioning from 1 g (Earth) to microgravity (spaceflight) and back, but the severity of responses vary by crewmember. Postflight symptoms are compounded and exacerbated the longer the crewmember spends in microgravity and affect manual dexterity and balance. These symptoms can be debilitating, affecting an astronaut's ability to perform mission-critical tasks, but typically resolve within a few days. Little data exists on the effects of transitioning from microgravity to partial gravity on the Moon (1/6 of Earth's gravity), and none exists for transitions to Mars gravity (3/8 of Earth's gravity).

The ISS4Mars International Organizing Committee's original concept for a Post-landing Assessment Use Case involved the entire crew performing autonomous tasks 0–60 hours after they returned from long-duration missions. The suggested tasks would simulate the actions that the crewmembers would be required to perform shortly after they land on the martian surface and involved self-administered health and performance assessments and rehabilitation measures. The suggested use case tasks and operations included vehicle egress, extravehicular activity, and manual control such as for telerobotics, which the ISS crewmembers would perform after they returned to Earth's gravity or to simulated martian gravity.

The MHRPE SG experts for this use case evolved the scenario to assess a team of two crewmembers performing an operational simulation to deploy a communication system after landing, which involved varying levels of postural challenge. The aim was to evaluate how the crewmembers assess themself and collectively accomplish complex tasks by assigning tasks based on their post-landing fitness level. The primary research objective was to evaluate how the performance of individual crewmembers is impacted by differing levels of deconditioning during an early post-landing timeframe. The secondary research objective was to monitor how the team distributes individual tasks, and how this distribution relates to individual fitness level, by capturing information about both individual and team performance. The new use case scenario incorporated lessons learned from the May 2003 Expedition 6 ballistic landing and delayed recovery time [9], underscoring that the success of a Mars mission will require crewmembers to work collaboratively as a team, each contributing within their own physical limitations. Although the original use case involved crewmembers having to egress the vehicle unaided after a long-duration spaceflight, flight operations members considered that this activity may be unsafe. Thus, the SG did not include unaided egress in their use case scenario.

NASA is currently leading the implementation of this use case, and some operational stakeholders still maintain concern about this scenario, arguing that it lacks fidelity to an actual Mars mission. The resources for maintaining fitness on the ISS may be greater than those on the Mars transit vehicle, which could lead to false success. False failures could also occur because the crewmembers will be tested in the higher Earth gravity level of 1 g rather than the 3/8 g of Mars. Discussions continue regarding how a higher fidelity simulation might be possible. The upcoming ISS decommissioning schedule (approximately 5 years from the date of this publication), however, drives agencies to evaluate postflight readiness to land on Mars and perform nominal or off-nominal operations while the ISS is still operating. Investigators are also exploring non-ISS research platforms, such as ground analogs of spaceflight and commercial spaceflight platforms coupled with postlanding testing for prework or substitution for an ISS4Mars use case application. The March 2025 success of the SpaceX Fram2 mission unaided egress of the capsule after flight may influence agencies to reconsider testing unaided egress after ISS astronauts return from a long-duration mission [10]. Planning is still complex and continues for this critical ISS4Mars use case.

4.3 Earth-Independent Medical Operations Use Case

Crewmembers will be much more autonomous on a mission to Mars than they are on the ISS. Because the communication delay from Mars to Earth (and vice versa) can extend to 24 minutes one way, access to medical expertise will be limited, making it difficult to receive timely guidance and feedback during medical interventions. In addition, the impossibility of an emergency return to Earth and limited access to medical technologies highlight the need to shift from a ground-based telemedicine approach to one that supports greater medical autonomy, which will include the ability for the crew to engage in Earth-independent medical operations. This approach will be complex, involving an onboard medical support system that includes key diagnostic and analytical equipment; therapeutic pharmaceutical, surgical and other methods; training and decision support; and medical data management.

The ISS4Mars International Organizing Committee's original use case suggested two crewmembers (patient and care giver) simulate nominal medical operations, such as monitoring a crewmember's health status, care, and nutritional needs, and then progressively simulating more complex medical emergencies. The simulations were envisioned to last up to two days, with communication delays, using relevant health and performance medical devices and data that are currently on board the ISS, and included the possibility of testing new solutions. Simulations would be thoroughly developed and tested on the ground before conducting them on the ISS: although medical operations in the absence of gravity ultimately requires testing in a microgravity environment, much of the evaluation of technical tools, processes, and data management can be accomplished on the ground first.

The MHRPE SG revised the Earth-independent Medical Operations Use Case to include an iterative series of scenarios to demonstrate and test various aspects of autonomous medical care across several ISS increments. Subsequent simulations would be designed to build on the previous ones by incorporating lessons learned and be more advanced in terms of activity types, complexity, novelty of the tools, and modified pre-mission training protocols. In the first operations scenario, a crewmember who has Chief Medical Officer-level training but who is not a professional physician would perform a comprehensive routine history and physical examination without ground communication or guidance and using current ISS tools and medical devices. In later scenarios, crewmembers with no Chief Medical Officer training would be the caregivers. The scenario is expected to reveal gaps in key procedures and pre-flight training.

The Canadian Space Agency (CSA) is currently leading the effort to develop and implement the Earth-independent Medical Operations Use Case(s) into operations on the ISS. The CSA team identified a need for clearer, more extensive procedural guidance that offers just-in-time clinical decision support while adapting to the crewmember's level of expertise. Consequently, they are modifying a ground-tested, commercial software from EZResus [11], which is widely used by healthcare practitioners around the world, for use on the ISS. The Advanced Astronaut Medical Support (ADAMS) app, the version adapted for space, will enable the crew to easily access procedures and just-in-time tutorials and to manually input data from ISS medical devices to create a comprehensive report that can be reviewed by the flight surgeons using the Everywear platform [12] CSA will first test this procedure in remote settings in Canada, such as James Bay, to improve and validate its use for remote healthcare [13]. As with all the ISS4Mars use cases, the timeline for decommissioning the ISS means that the team will likely be able to complete only one or two iterations on the ISS. In addition, the complexity of a fully autonomous medical system is much larger than the scope of this ISS4Mars use case and would need complete testing before a Mars mission.

4.4 Food System Use Case

With current propulsion capabilities, a mission to Mars will likely take a total of 2–3 years, and mass, power, and spacecraft volume will be limited. Resupply for such a mission is unlikely, requiring the crew to either bring all required consumables with them or have them pre-deployed. These consumables include food, which will be needed to not only provide calories, but also to maintain nutrition and mental health. The ISS4Mars International Organizing Committee's original use case related to food systems suggested a complex ISS4Mars assessment of an Earth-independent ECLSS, food, and autonomy scenario. The international MHRPE partners decided to simplify this use case to focus only on a Mars food system. The goal of the SG Food System Use Case is to extend studies of the Mars exploration food system that were conducted in ground analogs of spaceflight by testing them on the ISS over a one-year period, using the entire crew, and focusing on components (e.g., pre-packaged food) that are already developed to a level that is mature and appropriate for a Mars transit, surface, and return mission. Although the SG thought that other technologies for food production could be useful for spaceflight (e.g., 3D printing), they deemed the technology readiness level too low for deployment in a near term ISS4Mars simulation.

The resulting MHRPE SG experts' scenario evaluates the effectiveness and feasibility of an exploration-relevant food system for maintaining nutritional status. The food system would have 100% shelf stable foods (maintaining nutrition and palatability) based on the current ISS standard food system, supplemented with limited specialty items that meet exploration requirements and some "pick and eat" crops. This ISS4Mars use case would assess the nutritional status by analyzing the crewmembers' blood and urine biochemistry and their body composition, as well as their immune function, cognitive function, physical performance, and behavioral health. The expectation was that a reduced variety of food would result in menu fatigue and underconsumption, leading to physiological effects on body mass, immune function, and cognitive and behavioral health.

As the lead, NASA has been shepherding the further development of this use case for operations on the ISS; however, several challenges exist. For instance, the ISS crew may be reluctant to participate in this type of study, given their diet will be limited to only standard menu foods with no fresh foods from resupply vehicles for a long evaluation duration (6–12 months). This duration was selected because it more closely simulates a Mars mission and enables comparison of results with long-term ground-based analogs of spaceflight (e.g., studies conducted in the Crew Health and Performance Exploration Analog) [14]. Furthermore, if not all crewmembers agree to participate, i.e., some of the crewmembers participate and some do not, the crew may experience interpersonal issues within the team, or not fully comply with the study. In addition, crewmembers may not be able to consume bioregenerative crops that are generated during experiments in growth chambers on the ISS because some tests will result in plants unfit for human consumption. NASA is continuing to explore the possibility of employing a Food System Use Case on the ISS, however, they would first like to conduct further ground testing of a food system in long-term analogs of spaceflight and invite international (and commercial) partners to participate. Given the looming timeline for decommissioning the ISS, it is likely that the final ISS crew will be targeted for this ISS4Mars use case.

5. Lessons Learned and Future Considerations

The original ISS4Mars vision was to have a space laboratory environment capable of hosting an integrated, final, dry run of all key aspects and countermeasures to assess current readiness for a Mars mission. Over the past ten years, the international spaceflight community experienced multiple challenges implementing that vision, causing them to move slowly, and now they face the reality that implementation may be hampered by the approaching end of life for the ISS. None-the-less, the community has learned many lessons to enable future, more agile, Mars readiness testing.

Out of necessity, the ISS4Mars effort evolved from the original integrated test into methods to implement key, scaled-back multiple Mars risk-associated use cases, anticipating that these scenarios are potentially more achievable within the available ISS time frame. As mentioned, the initial integrated ISS4Mars effort was hampered because it began half-way through the lifetime of the ISS, and the ISS was not designed for that purpose. In addition, relevant already-planned single experiments were being conducted and would be affected by the ISS4Mars use cases. Although the international spaceflight partners are still attempting to prioritize, synchronize, and leverage each other's ISS studies, potentially down selecting some of the existing research, reaching an agreement among all ISS partners regarding the priorities of studies to be conducted on ISS before its end of life is challenging.

Ultimately, if the ISS is decommissioned before the use cases, or ideally an integrated ISS4Mars test, are completed, other LEO stations could support that type of testing. LEO-based testbeds are desirable because an ideal Mars analog platform in space should be easily accessible (e.g., close to Earth), spacious enough to accommodate a dedicated crew for extended periods, and capable of offering the highest possible fidelity in simulating space stressors and related, integrated, Mars-like capabilities and operations. Future LEO stations could have these capabilities if the planning begins early in the design phase. A LEO station could be used by a collective body of not only international space agencies but also commercial developers and users with a shared interest in human exploration of Mars. Ideally, these platforms could be designed to support an ultimate integrated Mars test. In anticipation, partners interested in using LEO as a Mars test bed could collaborate early to offer resources enabling ground studies first, when possible, and then to shape a Mars mission-like integrated test collaboratively on a future LEO station.

An unavoidable weakness of a LEO-hosted analog of a Mars mission is that LEO conditions are not identical to those of a Mars mission. For example, for postflight fitness assessments, returning to Earth may not be a perfect analog for landing on the surface of Mars after a transit flight because Mars gravity is 3/8 of that on Earth; however, devices to offload Earth gravity (e.g. Active Response Gravity Offload System, [15]) could be employed for some postflight analyses. In addition, the presence of the Earth's magnetic field largely shields solar particle events (SPEs) and thus limits comprehensive testing of countermeasures to protect against the effects of SPE exposure on the ISS. Therefore, the LEO environment is an imperfect, albeit accessible, radiation analog for a Mars mission. No spaceflight analog, however, is ever a perfect simulation of all mission-specific spaceflight hazards, but investigators strive to do the best possible and qualify conclusions given any data uncertainties.

Following a successful 10-year international collaborative effort for ISS4Mars, agencies are actively assessing the four use cases described earlier and developing them for implementation on the ISS. Partners are hopeful that at least some aspects of these studies can be completed on the ISS before it is decommissioned. If not, these use cases, or the integrated final test, can be studied on new commercial LEO stations when they become available. Success in this stepwise approach will provide not only extremely valuable insights into some of the most critical life-saving operations required during exploration-class missions but will also lay the groundwork for advancing toward a more demanding, full-scale, and potentially permanent LEO4Mars implementation strategy. The ISS4Mars initiative helped define the types of studies to be included in this strategy.

The exploration-focused global community needs a space-based platform to conduct an integrated test of the current level of knowledge, operations, and countermeasures in LEO before they venture on a human mission to Mars. This testing will require extensive planning. In principle, a successful final "dry run" of the Mars mission should be the last major activity before the actual mission. By working safely in proximity to Earth through the ISS4Mars or LEO4Mars approach, the space research and engineering community, international agencies, and commercial partners can develop the vehicles and tools necessary to enable not only human exploration of Mars, but also human progression further into the solar system.

Acknowledgements

The authors would like to thank the more than 100 colleagues from around the world who contributed to this work via the ISS4Mars International Organizing Committee, MHRPE, and the MHRPE Subject Matter Expert Splinter Groups.

References

[1] L. Narici, G. Reitz, The ISS as a platform for a fully simulated Mars voyage, HIS-15-PS3-2, 20th International Academy of Astronauts Humans in Space Symposium, Prague, Czech Republic, 2015, 29 June – 3 July.

[2] L. Narici, G. Reitz, C. Lobascio, Integrated simulation of Mars flights on the ISS, Adv. Space Res. 62 (2018) 990 – 996.

[3] J.B. Charles, M. Arya, C.E. Kundrot, Use of International Space Station to simulate interplanetary transit: Human health and performance applicability of current increment durations and extended durations, (2011) NASA/TM–2011-216143.

[4] J.A. Robinson, M.C. Waid, D. Korth, M. Rucker, R. Renfrew, Innovative approaches to using the International Space Station as a Mars transit analog, IAC-19.B3.3., Proc. 70th International Astronautical Congress, Washington DC, U.S.A., 2019, 21 – 25 October

[5] M. Waid, L. Narici, M. Girgenrath, K. Stang, I. Marcil, P. Johnson-Green, T.J. Ngo-Anh, O. Kotov, K. Murakami, R. Dempsey, J. McPhee, K. Sato, B. Siegel, S. Scimemi, 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, REACH - Reviews in Human Space Exploration, 27-28 (2022) 100047.

[6] J.A. Robinson, M.C. Waid, T.J Ngo-Anh, I. Marcil, B. Shishkov, K. Murakami, K. Stang, O. Kotov, V. Cotronei, L. Narici, V. Savinkov, M. Girgenrath, P. Johnson-Green, B. Siegel, K. Sato, S. Scimemi, R. Gatens, Novel ways to use the International Space Station as an exploration analog: International progress in planning 'ISS4Mars', IAC-21-B3.3.2, Proc. 72nd International Astronautical Congress, Dubai, United Arab Emirates, 2021, 25 – 29 October.

[7] S.S. Laurie, J.R. Lytle, S.K. Pickering, M.J. Poczatek, S.M.C. Lee, L..P Pardon, A.E. Miller, D.S. Martin, E. Mulder, S. Moestl, D. Pesta, T. Frett, C. Stern, J. Tank, J.N. Hoenemann, S. Sadda, R. Karanjia, K. Marshall-Goebel, M. Young, C.W. Cole, A.S. Huang, B.R. Macias, Daily use of countermeasures to prevent headward fluid shifts throughout 30 days of strict head-down tilt bed rest, J Appl Physiol (1985), 139 (2025) 394–413.

[8] Y. He, R. Karanjia, X. Zhang, D. Wanderer, E. Walker, S.H. Lee, M.J. Poczatek, C.S. O'Grady, K.M. Marion, M. Young, S. Moestl, E. Mulder, C. Stern, S.R. Sadda, S.S. Laurie, B.R. Macias, A.S. Huang, Optic nerve vasculature and countermeasure assessment in a bedrest analogue of spaceflight-associated neuro-ocular syndrome. Am J Ophthalmol. (2025) 278, 317–327.

[9] Science and Exploration, Crew 6 Ballistic Landing. December 5, 2003 https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/A_hard_but_safe_landing (accessed 09/03/2025).

[10] SpaceX's Fram2 astronaut mission return to Earth. April 4, 2025. https://www.youtube.com/live/MWBmcRl2UeI?si=KqeM1T5JJWT2OHJZ (accessed 09/03/2025).

[11] Canadian Space Agency, Deep Space Healthcare Challenge winner: Addressing medical emergencies in space and on Earth. February 28, 2024. https://www.canada.ca/en/space-agency/news/2024/02/deep-space-healthcare-challenge-winner-addressing-medical-emergencies-in-space-and-on-earth.html (accessed 09/03/2025).

[12] Science & Exploration, Everywear kit. November 9, 2017 https://www.esa.int/ESA_Multimedia/Images/2017/09/Everywear_kit (accessed 09/03/2025).

[13] The Cree Board of Health and Social Services of James Bay, Bush Kit with A.D.A.M.S. simulation in Whapmagoostui. April 15, 2025. https://www.creehealth.org/news/bush-kit-adams-simulation-whapmagoostui (accessed 09/03/2025).

[14] NASA, Crew Health and Performance Exploration Analog. https://www.nasa.gov/humans-in-space/chapea/ (accessed 09/03/2025).

[15] The NASA Technology Transfer program, mechanical and fluid systems: Full-Size Reduced Gravity Simulator For Humans, Robots, and Test Objects. https://technology.nasa.gov/patent/MSC-TOPS-60 (accessed 09/03/2025).