

Space Power

A Review to Assess the Challenges of a Human Mission to Mars

Dylan Charlton¹

¹ United States Army

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The phased strategy of the National Aeronautics and Space Administration (NASA) starting from Earth-reliant operations on the International Space Station (ISS) through proving ground missions in cis lunar space, all the way to Earth-independent deep space operations, provides a framework for planning human Mars missions. Recent developments, such as the selection of multiple industry proposals to study alternative, more efficient Mars Sample Return (MSR) methods, as well as new research on human factors from analog missions, provide updated insights that refine this framework. International and commercial partnerships have accelerated advances in propulsion, life support, habitat design and in situ resource utilisation, all of which are essential for supporting long-duration missions. However, significant challenges have also been identified, including radiation exposure, microgravity induced physiological changes and psychosocial stress. The purpose of this paper is to review the planning process and technological readiness for complex human exploration missions to Mars, incorporating considerations of space medicine, human factors, psychosocial impacts, radiation protection and ethical frameworks. This review is intended to inform mission investors and policymakers about the challenges and proposed countermeasures essential for a safe, reliable and ethically sound human journey to Mars. The anticipated establishment of a Mars base through the utilisation of a Lunar outpost as a crew launch and logistics platform further enhances mission feasibility and highlights the need for a multidisciplinary approach.

1. Introduction

Human space exploration has evolved dramatically since the early days of rocketry and lunar landings, setting the stage for increasingly ambitious missions beyond Earth orbit. In the 1960s and 1970s, the Apollo program established the possibility of human spaceflight by successfully landing astronauts on the Moon and returning them safely to Earth. These early milestones provided invaluable lessons in spacecraft design, life support and human physiology under extreme conditions. Over time, technological and scientific advances led to the development of the International Space Station (ISS), a multinational laboratory that has enabled continuous human presence in low Earth orbit (LEO) (National Aeronautics and Space Administration (NASA), 2015).

Building on the experiences gained from the ISS, space agencies have shifted their focus toward deep space exploration. Robotic missions on Mars have been particularly transformative, offering critical insights into the Martian environment. Orbiters, landers and rovers have mapped the Martian surface, analysed its atmospheric composition, and identified key resources such as water ice (NASA, 2015). These missions have not only deepened our understanding of Mars as a dynamic planet with a complex geological history but have also highlighted challenges such as ex-

treme radiation levels, pervasive dust storms and the effects of reduced gravity (Nicogossian et al., 2016). In recent years, NASA has begun reevaluating the architecture of its Mars Sample Return (MSR) campaign to reduce complexity and cost, selecting multiple commercial concepts for study in 2024 and initiating two concurrent landing design options in early 2025 (NASA, 2025b; Wilcox, 2025). Additionally, analog missions such as the Crew Health and Performance Exploration Analog (CHAPEA) are contributing valuable real-time data on isolation, resource constraints and psychological performance in Mars-like environments (NASA, 2024a).

The current knowledge base highlights that Mars, while promising as a target for human exploration, presents a host of formidable challenges. Physiologically, astronauts are known to suffer from muscle atrophy, bone density loss and cardiovascular deconditioning during long-duration spaceflight (Evans et al., 2018; Nicogossian et al., 2016; Stavnichuk et al., 2020). Studies indicate that even Mars's partial gravity, which is only approximately one-third that of Earth's, may not be sufficient to prevent these adverse health effects (Hodkinson et al., 2017; Nicogossian et al., 2016). Psychologically, the isolation and confinement inherent in extended missions can lead to increased stress, cognitive decline and interpersonal conflicts (Kanas et al., 2001). Research in space psychology emphasises the im-

portance of developing robust countermeasures, including artificial intelligence (AI) driven mental health monitoring and virtual reality-based resilience training, to support crew wellbeing (Friedman & Bui, 2017; Sharp et al., 2025; Vakoch, 2011). Recent analog studies further highlight that crew adaptability, interpersonal cohesion and workload balance are critical determinants of mission success in long-duration confinement scenarios (De la Torre et al., 2024).

Technological readiness has advanced considerably, particularly in the development of closed loop life support systems, which aim to recycle oxygen, water and waste to reduce dependency on Earth-based resupply (Marshall Porterfield et al., 2025). Innovations in in situ resource utilisation have shown promise in enabling astronauts to extract and process local resources for food, water and fuel, thereby enhancing mission sustainability (Cubo-Mateo et al., 2020). Emerging research also explores biologically driven construction materials and synthetic microbial systems to improve habitat resilience and reduce launch mass requirements (Onofri et al., 2025). Additionally, the exploration of artificial gravity solutions, like centrifugal force systems, is ongoing, as researchers seek methods to counteract the damaging effects of prolonged microgravity (Hodkinson et al., 2017). Furthermore, recent experimental data from 2025 indicates that shorter daily exposure to artificial gravity may not sufficiently preserve cognitive and neuromotor function, suggesting that longer or continuous exposure periods could be necessary, further cementing the need for improved technology in this field (Tays et al., 2025). These technological innovations are critical to the feasibility of a human round trip mission to Mars, as they directly impact the safety, reliability and overall success of long-duration human spaceflight.

The evolution of NASA's strategy reflects a phased approach to deep space exploration, progressing from Earth-reliant operations on the ISS to an established Lunar outpost. The Lunar outpost will serve as a staging ground and logistics hub, reducing risks by allowing for the prepositioning of supplies and crew resupply operations prior to embarking on a Mars mission (NASA, 2015). New policy reviews and architectural studies released in 2024 reaffirm this phased approach, emphasising cost reduction through commercial partnerships and the use of lunar infrastructure as a proving ground for Mars systems (NASA, 2024b). This strategy not only leverages decades of experience in space operations but also fosters international and commercial partnerships that are essential for sharing the significant costs and risks associated with human Mars exploration.

Understanding the historical context and current knowledge base is crucial because it highlights both the immense progress made in space exploration and the significant challenges that remain. The insights gained from decades of robotic missions and ISS operations inform the ongoing development of countermeasures and technologies that will be vital for future human missions to Mars. Moreover, historical context highlights the importance of continued investment in research and development, as well as the need for robust international collaboration and regulatory

frameworks to ensure that missions are both safe and ethically sound (Nicogossian et al., 2016).

This review aims to assess current knowledge regarding human Mars missions. The review incorporates NASA's 'Journey to Mars' roadmap, peer-reviewed journal articles, government publications and spaceflight industry reports. In total, 34 peer-reviewed articles, government reports and commercial studies published within the last two decades, with a few exceptions, were selected based on methodological rigour and relevance. Government reports, including NASA's strategic documents, provided robust evidence based on extensive mission data and long-term studies. Other sources contributed good evidence on emerging technological solutions for life support and habitat design. The overall strength of evidence across the selected publications is high, supporting NASA's phased approach to Mars exploration and the associated risk mitigation strategies. The planned Lunar outpost is expected to serve as a critical logistical hub, while advances in space medicine including real-time health monitoring and AI-assisted diagnostics mitigate many of the physiological and psychological challenges of long-duration missions. These integrated findings offer potential investors, policymakers and other stakeholders a comprehensive view of the technical, ethical and logistical challenges to be addressed.

2. Literature review

The literature reviewed for this study highlights a multifaceted array of challenges associated with a human mission to Mars. The main findings reveal that technological, medical and ethical factors are deeply intertwined. For example, certain experimental studies provide strong evidence that advanced radiation shielding through innovative garments and pharmaceutical interventions can mitigate cosmic radiation risks (Baiocco et al., 2018; Montesinos et al., 2021). However, the cumulative radiation exposure over a multi-year mission remains a critical unresolved issue. Additionally, systematic reviews confirm that the adverse physiological effects of prolonged microgravity such as muscle atrophy, bone density loss and cardiovascular deconditioning persist even under partial gravity conditions, as would be experienced on Mars (Hodkinson et al., 2017). Psychological challenges further compound these issues, as extended isolation and communication delays are likely to exacerbate stress, cognitive decline and interpersonal conflicts (Friedman & Bui, 2017; Vakoch, 2011). These findings collectively highlight that while significant progress has been made, several research gaps must be addressed before a mission can be deemed safe and reliable.

2.1. Technological factors

From a technological standpoint, integrating contrasting systems into a cohesive and fail-safe mission architecture represents the most significant challenge. The integration of advanced radiation shielding, closed loop life support, artificial gravity and in situ resource utilisation into a single operational system is essential for ensuring crew safety and mission success (Evans et al., 2018; Langell et al., 2008;

Marshall Porterfield et al., 2025). Recent updates to the MSR architecture prove a growing reliance on modular and commercially adaptable systems to increase resilience and reduce overall cost (NASA, 2025b; Wilcox, 2025). Other studies demonstrate that while individual systems show promise under controlled conditions, their combined performance under deep space conditions remains largely untested (Cubo-Mateo et al., 2020; Hodkinson et al., 2017). Moreover, the requirement for self-sufficiency given the impossibility of rapid re-supply during a Mars mission further complicates system integration. Technological innovation must therefore be coupled with rigorous testing in both simulated environments and transitional platforms, such as Lunar outposts, which are expected to serve as precursors to Mars missions (NASA, 2015). Future research should prioritise the development of modular technological systems that can function independently but interconnect seamlessly with other subsystems when required. Modularity to this degree would enable fault isolation, rapid reconfiguration and resilience in the event of a partial system failure. Research could explore AI-driven diagnostics and self-repairing materials to enhance autonomy during long-duration missions (Dremann et al., 2025; Prasad, 2025). Additionally, system verification campaigns on future Lunar outposts should focus on cross-system integration testing to validate life support, power and propulsion interoperability under realistic deep space conditions.

2.2. Medical factors

Medical and psychological support systems are equally critical to mission success. Evidence suggests that even modest improvements in countermeasures, such as the implementation of AI-assisted health monitoring and virtual reality-based psychological support, could yield significant benefits in maintaining crew performance during extended missions in both LEO and during interplanetary missions (Friedman & Bui, 2017; Kolluri, 2016; Sharp et al., 2025; Vakoch, 2011). Recent interdisciplinary reviews on human factors in space exploration stress that workload design, crew autonomy and social cohesion must be integrated into future Mars mission protocols (De la Torre et al., 2024). However, individual variability in responses to long-duration spaceflight implies that personalised interventions will be necessary. Future research should focus on developing adaptive countermeasures that can be tailored to the specific needs of each crew member, thereby enhancing overall mission resilience. Specifically, research should investigate adaptive countermeasures through dynamic physiological monitoring, where AI systems adjust exercise loads, nutritional intake and rest schedules based on real-time biometrics (Kolluri, 2016; Prasad, 2025). Another promising direction involves behavioural adaptation training, preparing astronauts to respond autonomously to psychological stressors using mission-specific virtual reality simulations and mindfulness conditioning (Finseth et al., 2025; Sharp et al., 2025). These approaches could be refined through extended CHAPEA-type analog missions that emulate multi-year confinement and communication delays.

2.3. Political factors

Beyond the technical and physiological aspects, the political climate is increasingly supportive of deep space exploration (Corrado et al., 2023). Globally, national space agencies and commercial entities are forging partnerships to share the immense costs and risks associated with Mars missions (Levchenko et al., 2018). Recent policy analyses reaffirm this trend, showing that public-private collaboration is central to NASA's revised MSR strategy and Artemis integration roadmap (NASA, 2025a). For instance, NASA's phased strategy that ranges from Earth-reliant operations on the ISS to the planned Artemis program and subsequent Earth-independent deep space operations has received broad international backing (NASA, 2015). Collaborations with the European Space Agency, Roscosmos and emerging commercial players like SpaceX have fostered an environment where resource sharing and expertise pooling are not only feasible but also essential. Despite this supportive backdrop, challenges persist due to fluctuating budgets, shifting policy priorities and geopolitical tensions that may affect long-term funding and strategic direction (Nicogossian et al., 2016). Recent reviews emphasise that sustained international coordination will be crucial to protect mission timelines and mitigate political volatility, particularly as commercial actors play a larger role in mission logistics and infrastructure (Corrado et al., 2023). These political uncertainties necessitate the development of resilient and adaptable mission architectures that can withstand changes in the international and domestic political landscape. To address these uncertainties, future research should explore adaptive governance and funding models. For example, mission architectures designed with modular international participation, where each partner contributes a functionally distinct but interoperable module (e.g., propulsion, habitat or logistics). This framework would allow mission progress even amid political shifts. Studies could also analyse long-term public-private associations as mechanisms for continuity in funding and technical expertise despite fluctuating political priorities.

2.4. Ethical factors

Ethical considerations form another cornerstone of the discourse surrounding human Mars missions. The reviewed literature consistently emphasises the importance of preventing both forward contamination from Earth to Mars and backward contamination from Mars to Earth. Comprehensive frameworks of ethical guidelines and health standards that serve as a foundation for long-duration spaceflight have also been created to prevent this from happening. These guidelines mandate stringent sterilisation protocols and quarantine measures to protect planetary environments (Kahn et al., 2014). Additionally, multiple reviews of planetary protection knowledge gaps identify more areas of concern for human missions, including biological contamination from habitat systems, medical waste management and long-term crew microbiome alterations (Fairén et al., 2019; Pugel & Rummel, 2025; Spry et al., 2024). Moreover, the remote and autonomous nature of a

Mars mission exacerbated by communication delays raises critical ethical issues concerning astronaut autonomy in emergency medical decisions (Kahn et al., 2014). The requirement for astronauts to operate with a high degree of self-reliance introduces ethical dilemmas regarding the extent of pre-mission training and the development of on-board medical decision-making tools (Kahn et al., 2014; Kolluri, 2016). Future research should examine applied ethical frameworks for autonomous medical triage and AI-supported decision systems to ensure that crucial decisions made under communication delays align with mission values and medical ethics. Further inquiry into crew ethics training protocols, including simulation-based moral reasoning scenarios, could provide practical models for autonomous decision making under isolation. Thus, ethical frameworks must evolve in tandem with technological advances to ensure both the safety of the crew and the integrity of extraterrestrial environments are maintained.

2.5. Legislative factors

The legislative background of space exploration is also in a state of evolution. The Outer Space Treaty and subsequent international agreements provide a broad legal framework for activities in outer space, but they are not sufficiently detailed to address the complexities of long-duration human missions to Mars. Current legislative instruments do not fully account for issues such as resource ownership, liability in the event of mission failure or the specifics of in situ resource utilisation on extraterrestrial bodies (United Nations Office for Outer Space Affairs, 1966). NASA's 2024 policy revisions and international working group reports have emphasised the need for clearer frameworks governing extraterrestrial construction, mining and data-sharing protocols (NASA, 2025a). As new technologies and mission architectures emerge, there is a pressing need for updated regulatory frameworks that offer clear guidelines on issues ranging from habitat construction and radiation safety to the ethical treatment of crew members during autonomous operations. Recent legislative commentaries also call for harmonisation between the Committee on Space Research (COSPAR) planetary protection standards and national commercial spaceflight laws to reduce jurisdictional ambiguity and ensure consistent planetary stewardship (Spry et al., 2024). Additionally, recent strategic documents suggest that legislative reform will be necessary to support the transition from Earth-reliant to Earth-independent operations (NASA, 2015; Nicogossian et al., 2016). Such reforms must be developed through international consensus, balancing the interests of multiple stakeholders and ensuring that legal standards keep pace with rapid technological innovations. Future studies could focus on developing adaptive legal templates for Mars operations, outlining dynamic treaties that evolve as technologies mature. Research into interoperable legal mechanisms for private sector involvement, modelled on existing governance frameworks such as the Antarctic Treaty, International Telecommunications Union or International Seabed Authority may offer practical blueprints for regulating resource use and liability on Mars (De Zwart et al., 2023).

3. Limitations and bias

Despite an extensive body of research, several limitations persist. Many studies on the physiological and psychological effects of long-duration spaceflight are based on small sample sizes and data from a limited number of astronauts, which constrain the generalisability of their findings (Friedman & Bui, 2017; Vakoch, 2011). In addition, many proposed technological solutions such as artificial gravity systems and advanced radiation shielding have primarily been tested in simulated environments, making their long-term performance in actual deep space conditions unverified (Hodkinson et al., 2017; Montesinos et al., 2021). The subjective nature of qualitative evidence assessment further introduces potential bias, highlighting the need for larger, more diverse studies and extended experiments that closely mimic the conditions on Mars. More recent analog missions, including CHAPEA, aim to close this gap by generating long-duration datasets on crew physiology, cognition and team dynamics in Mars-like environments (2024; NASA, 2024a). Future studies should aim to utilise extended analog missions and in-orbit testbeds that simulate deep space radiation and gravity gradients, providing higher fidelity physiological and behavioural data. Research teams should develop adaptive study designs capable of integrating longitudinal biometric monitoring to capture dynamic health trends over multi-year missions.

Existing legal frameworks and ethical guidelines also present notable limitations. Although the Outer Space Treaty provides a broad framework for planetary protection, it does not fully address the complexities of resource utilisation, liability or long-term habitation on Mars. Moreover, current ethical standards, while evolving, may not adequately resolve issues such as astronaut autonomy during emergencies or the management of cross contamination between Earth and Mars (Kahn et al., 2014). Multiple recent planetary protection gap assessments identified emerging bioethical and contamination-control challenges that require new international agreements and adaptive mission protocols to ensure sustainable interplanetary operations (Fairén et al., 2019; Pugel & Rummel, 2025; Spry et al., 2024). These legal and ethical constraints, combined with the research gaps in long-term exposure effects and integrated system reliability, limit our ability to fully ensure the safety and sustainability of Mars missions. Future research should aim to bridge these gaps, refining both technological countermeasures as well as legislative and ethical frameworks to support safe and responsible interplanetary exploration. For instance, policy research could evaluate legal frameworks for autonomous decision making, defining accountability structures for crew AI systems. Comparative studies could examine how terrestrial disaster response governance models might inform Mars mission autonomy policies, ensuring ethical balance between crew safety and independence.

4. Conclusion

The extensive review of the literature reveals that many of the proposed countermeasures and technologies for a

human Mars mission are supported with compelling evidence (Corrado et al., 2023; Levchenko et al., 2018). Studies on radiation shielding, life support systems and the physiological challenges of microgravity all consistently demonstrate promising results that, if further developed, can substantially mitigate the inherent risks of deep space travel (Baiocco et al., 2018; Cubo-Mateo et al., 2020; Hodkinson et al., 2017; Montesinos et al., 2021). Furthermore, research published between 2024 and 2025 provides new insights into human adaptability, sample return design and synthetic biology applications, suggesting that progress is accelerating in several critical domains (Onofri et al., 2025; Wilcox, 2025). Additionally, proposed ethical frameworks and guidelines offer a solid basis for formulating policies that ensure planetary protection and crew autonomy (Kahn et al., 2014). Research should prioritise integrated testing of interdependent systems on long-duration analog missions, focusing on operational resilience, modular functionality and crew autonomy. Further inquiry into AI-assisted habitat management, biological recycling systems and modular emergency medical units could provide actionable pathways to operational readiness. Political research should also assess multi-layered governance structures that balance national interests with sustained collaboration across decade-long missions.

These findings refine earlier assumptions about the feasibility of human exploration by demonstrating tangible advances in cross-sector collaboration, analog validation and in situ resource use. However, the evidence suggests that while individual components such as advanced shielding garments and closed loop life support show high potential, their integration into a cohesive, self-sufficient system remains an area requiring further research (Cubo-Mateo et al., 2020; Marshall Porterfield et al., 2025). Nevertheless, the applicability of these findings to recommended policy is evident. A coordinated, interdisciplinary approach that combines technological innovation with rigorous ethical

and legislative oversight is critical for establishing standards for future Mars missions. Continued emphasis on multi-domain collaboration between engineers, policy analysts and behavioural scientists will help bridge persistent gaps and generate testable frameworks for long-duration mission feasibility. Incorporating recent findings, CHAPEA results and emerging biological construction technologies demonstrate that mission feasibility now depends on real-time adaptability, strong international partnerships, and a balance between safety and sustainability. Continued investment across these areas will be essential to enable a safe and enduring human presence on Mars.

In summary, the integrated findings from the literature indicate that a human mission to Mars by the next quarter century is feasible but fraught with complex challenges that span technological, medical, political, ethical and legislative domains. The prevailing political support and ongoing international collaborations provide a positive backdrop for these missions (NASA, 2015; Nicogossian et al., 2016). However, evolving regulatory frameworks and consistent funding remain essential for transitioning from theoretical models to operational systems. Ethical guidelines must be robust and adaptive, ensuring planetary protection and crew safety, while technological innovations need to be rigorously validated in realistic operational environments. Overall, the strength of the evidence supports the adoption of robust standards and policies that prioritise safety, sustainability and ethical considerations, while highlighting the need for ongoing interdisciplinary research to address existing gaps. Only through continued interdisciplinary research and strategic policymaking can the multifaceted challenges of a Mars mission be successfully addressed.

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