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Risk trade-space analysis for safe human expeditions to Mars

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ABSTRACT

We assessed the integrated safety, health, and performance risk to crews on long-duration missions, specifically to Mars. Using a systems approach rather than one focused on individual countermeasures, we examined the trade space around several such risks to identify high-potential risk mitigation strategies and characterize aspects of Mars mission architectures that could lower aggregated risk. Current Mars Design Reference missions would require durations well over two years and would increase crew exposure to radiation and microgravity well beyond ISS levels, likely resulting in significantly reduced performance beyond our current capability to mitigate that could jeopardize mission success. A "fast Mars transit" round-trip mission concept was studied using an innovative flight dynamics approach to quantify the minimum total mission energy required for a Mars transit with total mission duration less than 400 days. This approach holds promise for sending humans to Mars and returning them safely with acceptable, potentially mitigatable, exposure to microgravity and radiation using current or near-term technologies. The fast transit concept would also result in fewer time-driven vehicle failures and enable sustainable deployment of humans and infrastructure to Mars on a regular cadence, allowing steady exploration and colonization of Mars. Finally, we conclude that reliance on the Low Earth Orbit (LEO) mission operations paradigm – i.e., one of near-complete real-time dependence on experts at Mission Control to manage the combined state of the mission, vehicle, and crew – is high risk given the communication delays and limited resupply of any Mars mission, and this risk is not eliminated by the shorter missions durations of fast transit scenarios. Based on historical trends, it is highly likely that the crew will face a high-consequence problem of uncertain origin during Mars transit when ground support will be greatly reduced. While it may be possible to reduce anomaly rates through improved reliability analysis and testing, and to reduce anomaly impacts through added robustness, such mitigations address only known failure modes and known uncertainties. Therefore, a radical shift in the Human-Systems Integration Architecture (HSIA) that defines the operational paradigm, systems design, and human-systems interactions is required to improve the risk posture to an acceptable level regardless of mission duration.

1. Introduction

Planning is underway at NASA for returning humans to the Moon, followed by human missions to Mars. Humans will again venture outside the protective particle radiation shield of the Earth's magnetosphere, this time for durations of months to several years, where they will be vulnerable to long-term exposure from galactic cosmic rays (GCRs) and particles associated with solar storms. Mars missions will leave behind the real-time support of Mission Control and the ability to send spare parts or quickly return crew to Earth in an emergency. Interplanetary mission durations of up to 1000 days in space bring new uncertainties, regarding not only the impact of microgravity and radiation on human health and performance, but also the ability for crew to anticipate and respond autonomously to spacecraft system failures.

The NASA Engineering and Safety Center (NESC) recently performed a first of its kind study focused on assessing **integrated safety, health, and performance risks** to crew on long-duration expeditions beyond low Earth orbit (LEO), **specifically missions to Mars**, and the potential

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engineering solutions required to minimize those risks. Using a systems approach rather than one focused on individual countermeasures, the NESC assessment team examined the trade space for a subset of human spaceflight hazards and the associated risks to identify solutions to mitigate the risks to crew on missions to Mars. That assessment was intended to inform characteristics of those Mars mission architectures that render the lowest integrated safety, health, and performance risk. The analysis and results of the NESC assessment are fully documented in a NASA Technical Memorandum Document [1]. This paper contains content that has been adapted from that report but expands beyond it to discuss the risk-tradeoffs and future challenges of Mars missions in greater detail.

2. Spaceflight hazards

Deep-space exploration missions to the Moon and ultimately Mars will present new tests of astronaut safety, health, and performance. Hazards increase as missions increase in duration and progress farther from LEO. The NASA Human System Risk Board (HSRB) and the Human Research Program (HRP) have worked to define and mitigate the human safety, health, and performance risks associated with spaceflight. From those efforts, five hazard categories were identified: 1) Altered Gravity Fields; 2) Distance From Earth; 3) Radiation; 4) Isolation and Confinement, and; 5) Hostile/Closed Environments [2] (see Fig. 1). Within each of these hazard categories lie several associated risks (probability of a particular adverse outcome). This assessment focuses on risks associated with radiation, altered gravity, and distance from Earth, and their integration, to identify gaps that might be closed through engineering solutions for Mars missions (i.e., at least 1 year or more).

2.1. Radiation

Exposure to radiation has the potential to cause in-mission health, in-mission performance, and long-term health (LTH) consequences. When venturing into cislunar or interplanetary space for long durations, radiation hazards of solar particle events (SPEs) and GCR are encountered. For SPEs originating from solar flares and coronal mass ejections (CMEs), the duration of the events can last from a few hours to several days with an intense fluence of relatively low-energy particles. The greater threat is from SPEs generated by CMEs that can last for a day or two and multiple CMEs over a period of days to a week. GCRs are high-energy, pervasive low-flux particles with much lower fluences; long exposures increase cancer risk and may cause cardiovascular disease (CVD) and central nervous system (CNS) decrements on long duration missions.

2.2. Microgravity

Extended durations in microgravity lead to physiological deconditioning if not appropriately mitigated, with potential impacts to crew health and mission objective performance. Eleven individual health risks are directly tied to prolonged microgravity exposure, including cardiovascular and muscular deconditioning, skeletal demineralization, neuro-ophthalmological degeneration, and sensorimotor adaptation. Some altered gravity risks (e.g., spaceflight associated neuro-ocular syndrome (SANS)) are unique and currently lack broadly accepted countermeasures [3–5].

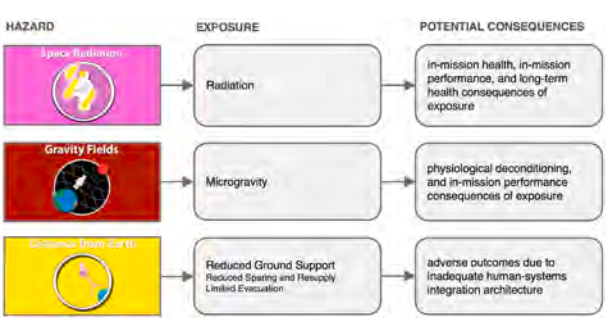

Fig. 1. Hazard categories 1, 2, and 3, and their potential consequences for Mars missions.

2.3. Reduced ground support (distance from earth)

NASA's mission operations paradigm of near-complete real-time dependence on experts on Earth to manage the combined state of the mission, vehicle, and crew, originated with Project Mercury and has endured with minimum evolution through Apollo Program, Space Shuttle Program, and ISS missions. Throughout this 60 year history, problem-solving and decision-making have been almost entirely carried out by Mission Control (MC). Similarly, execution of complex and/or safety-critical procedures in space has been done with intensive ground support and oversight. This includes in-mission maintenance activities that are heavily scripted and directed by the ground and that rely mostly on orbital replacement units (ORUs) that are launched on an as-needed basis to avoid intricate onboard repairs. While successful for near Earth exploration, this model is not viable for long-term missions to the moon and beyond. Increased distance from Earth with attendant communication delays and architecture challenges reduces the availability of resources from resupply and on-board stores, and the availability of information and decision-making resources from MC. Mission abort and evacuation scenarios may also be severely limited. The mission operations Human-Systems Integration Architecture (HSIA) will need to be radically changed from its current instantiation to support such Earth independence. The risk associated with the distance from Earth hazard is that extended missions beyond low Earth orbit will have inadequate capability in the integrated human-system to execute complex operations (e.g., corrective maintenance) and respond to anomalies, leading to adverse outcomes. This risk is also known as the risk of adverse outcomes due to inadequate HSIA (i.e., the HSIA risk).

3. Human risk assessment

On any future deep-space mission, crew capability will steadily decrease over time due to cumulative degradation of physiological and psychological function from a wide array of spaceflight-specific hazards. This can lead to a decreased ability to perform operational tasks necessary for mission success and, in the worst cases, negatively impact both crew health and safety during the mission and even potentially their long-term health (LTH) after the mission is over. It is currently unclear how well crew capability can be maintained during a Mars mission, but, within any current Mars Design Reference Mission scenario [6], in many categories, it will degrade beyond our historical experience, especially upon reloading to Mars gravity after an extended period of weightlessness. In addition, as distance from Earth increases, the safety net of ground support will degrade as a Mars mission progresses and be maximally compromised at the time of greatest need (upon arrival and landing on Mars and during crew surface activities).

This section explores the current understanding of the multidimensional risk space associated with three key hazards: microgravity, radiation, and distance from Earth (reduced ground support). It should be acknowledged at the onset 1) that these three hazards are not the only ones, 2) that the many known hazards may have unknown interactions that could further magnify overall risk, and 3) that there may be unknown additional human-system risks from these hazards that emerge for the first time in the context of Mars missions, given the exposures and durations are far beyond our current knowledge and experience base.

To examine risk trends, each risk is depicted as a function of mission duration. For this study, risk is defined as the probability of either in-mission or post-mission outcome measures: i.e., in-mission outcomes of loss of mission objectives (LOMO) and potentially of the entire mission (LOM) or of the crew (LOC), or post-mission outcomes related to long-term health (LTH) outcomes (e.g., medical conditions and quality-of-life impacts).

Risk due to the radiation hazard will increase with mission duration due to the increased time of exposure and the loss of the protective effects of Earth's magnetosphere (Fig. 2). This primarily affects the risk of radiation-induced carcinogenesis in the LTH domain with suspected contributions to CVD and CNS decrements that, even if they do not reach clinical levels, could nonetheless impact mission operations. Fig. 2 shows the notional radiation risk trend as a function of mission duration, culminating in about a 2–4.5% Risk of Exposure Induced Death (REID). This cumulative risk is relatively well understood as there are integrated models of radiation exposure from long-term ground-based data. Although the unknown risk of in-mission cognitive impacts due to CNS degradation from radiation exposure is not anticipated to be serious, further research in this area is warranted to properly assess the risk to crew performance in the context of a Mars mission. While rodent models of neural effects can characterize generic impacts on the health and functioning of mammalian neurons, research using non-human primate models of higher-order sensorimotor, spatial reasoning, and cognitive function could be used to better predict potential impairment of human performance due to sustained radiation exposure (see e.g., Refs. [7, 8]). Fig. 2 also highlights the fact that shorter fast-transit mission designs or enhanced shielding technologies would *de facto* mitigate this risk, although it is not likely that it could be reduced to the level that NASA currently accepts on ISS.

Risk due to the altered gravity hazard will increase with mission duration due to the increased time of exposure (Fig. 3). This primarily affects the risk of microgravity-induced physiological deconditioning in the LOMO/LOM domain. The trends presented in Fig. 3 are notional predictions based on severely limited data from missions in Low Earth Orbit, gathered nearly exclusively from missions lasting less than 7 months. Further research is needed to characterize various potential consequences of altered gravity on vision, sensorimotor coordination, cardiopulmonary condition, musculoskeletal strength, and cognition for the exposures expected during long-duration Mars missions.

Fig. 3 also illustrates that full Artificial Gravity (AG), i.e., the successful restoration of Earth 1g gravity 24/7, by definition, would effectively eliminate the hazard and thus the risk. It is also likely that some limited regiment of partial gravity (either less than 1g and/or for less than 24/7) could also provide significant risk reduction, but this more nuanced approach would require extensive research to validate the appropriate parameters—optimally it would require a space-based centrifuge for validation. A partial gravity mitigation regime could possibly be initially validated piecemeal on Earth using validated microgravity analogs (i.e., 6 deg head-down bedrest) and various partial gravitational reloading techniques (e.g. periodic time upright or lower-body negative pressure) for each of the component risks (i.e., vision,

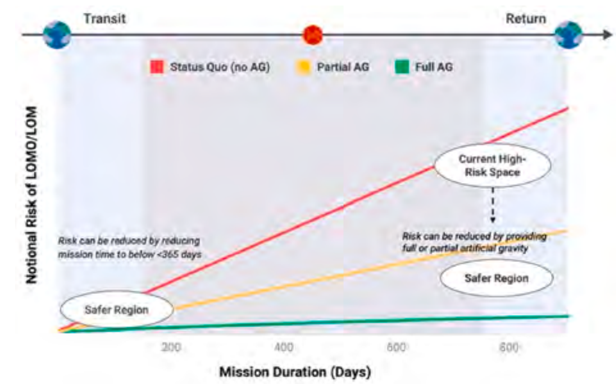

Fig. 3. Notional microgravity risk trends showing current risk trade-space and illustrating the benefits of shorter fast-transit missions or restorative artificial gravity systems (partial or complete) and other mitigation technologies.

cardiovascular, etc.) (see e.g. Ref. [9]). However, without the availability of a space-based human-rated centrifuge, the ability to develop and fully validate viable and integrated partial gravity countermeasure technologies is severely constrained.

Risk due to the distance from Earth hazard (Fig. 4) will indirectly be a function of mission elapsed time as the increasing distance during transit to Mars will cause increasing delays/losses in communication and quickly eliminate the option of resupply and evacuation. As depicted in Fig. 4, the blue line shows the cumulative probability of a significant anomaly occurring increasing throughout the duration of the mission (based on the historical ISS average rate of 1.7 significant anomalies/year). Such anomalies bear consequences ranging from LOM to even LOC. The red solid line in the figure shows the notional cumulative probability of an *unresolved anomaly* occurring (i.e., an anomaly that the crew-vehicle system is unable to resolve with the onboard HSIA). This trend is affected by the change in one-way communications delay throughout the notional mission as depicted by the yellow line. Because the largest communications delay is experienced near the middle of a Mars mission (i.e., peak distance from Earth), the darker grey box indicates the domain where round-trip communication delay requires the crew move to a more autonomous operational paradigm than has been experienced before in human spaceflight.

As suggested by the dotted red line, the risk associated with anomalies could be significantly reduced by novel crew-controlled mitigation strategies supported by new, yet to be developed, onboard support systems [1]. Fig. 4 also illustrates that fast transit would *de facto* reduce the integrated failures by a factor of 2–3 and thus reduce the HSIA risk. However, even a one-year mission would not overcome the communication and resupply constraints, so significant progress in HSIA will be

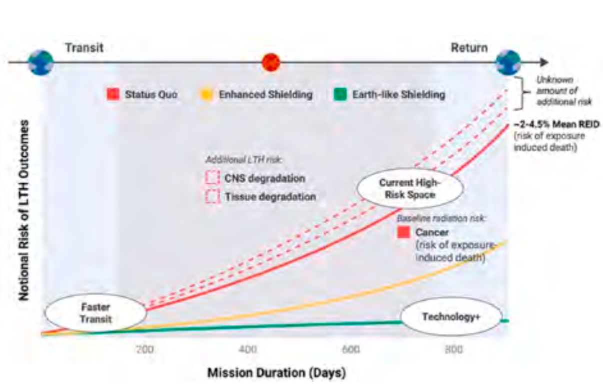

Fig. 2. Notional radiation risk trends showing current risk trade-space and illustrating the benefits of shorter fast-transit missions or enhanced shielding technologies.

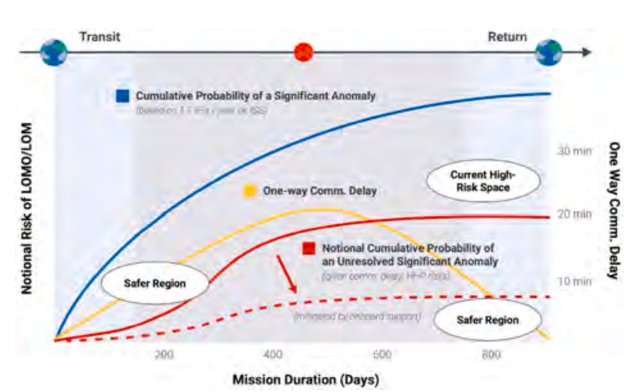

Fig. 4. Notional HSIA risk trends showing current risk trade-space and illustrating the benefits of shorter fast-transit missions or supportive technologies that increase the capabilities of the onboard human-system team [1].

necessary, regardless of mission duration, as bending the righthand trend risk curve downward will be very difficult for any Mars mission. Using the LEO concept of operations (the current HSIA) despite the large communication delays/losses and the impossibility of resupply would result in high risk in any Mars mission scenario. Research and development related to validating novel deep-space HSIA solutions will be required for success for any crewed mission at extended distances from Earth.

The shape of the solid red line in Fig. 4 is hypothetical, attempting to represent the combined effects of increasing probability of anomaly occurrence and varying communication delay (i.e., ground support) throughout the mission. Its shape is also influenced by other variables that affect mission resilience (Fig. 5), including:

- **System knowledge:** Crew knowledge and confidence in the vehicle systems are likely to increase throughout the mission as they encounter and deal with anomalies.
- **Spares and consumables:** Spare parts for maintaining and repairing critical systems and consumables, including medicines, are depleted as the mission progresses. If these are not available or cannot be made, the options for mitigating issues decrease.
- **Training and performance:** These show a similar trend to spares; as time continues, the effectiveness of pre-mission training wanes. If in-mission training is realized as part of vehicle systems, then this risk can be mitigated.
- **Evacuation (EVAC):** Options for evacuation (or abort) in the case of a vehicle failure or health issue decrease dramatically soon after launch to Mars [10].

These factors are further exacerbated by reductions in crew capabilities due to the radiation and microgravity hazards.

4. Integrating across multiple risks

Integrating across multiple risks is difficult as the risks are not independent and thus do not simply add. Any predictions (see Fig. 6) are therefore tentative and notional. Furthermore, as we extrapolate risk beyond our current knowledge base (downward black arrow in Fig. 6), we do not know the exact shape of the expected trend; there is considerable uncertainty that increases as mission duration extends further beyond the current data, especially from the altered gravity hazard. More specifically, we do not know if the effects of the combined spaceflight hazards on safety, health, and performance will saturate, increase linearly, or even increase exponentially as mission duration extends beyond a year (see solid blue lines in Fig. 6). Indeed, given that the data on human deconditioning are clustered around standard STS and ISS mission lengths, we essentially only have 3 effectively independent data points that we can fit (at ~2–3 weeks, at ~3–7 months, with the added assumption of zero risk for zero duration). While there are some data at the 1-year time point, it is limited to only a few crewmembers and thus is very preliminary. Thus, many two-parameter models (ones with a hard saturation or plateau, ones with a soft saturation or decreasing slope, and potentially even ones that do not saturate or even increase their slope) can provide good fits to the data, leaving the shape of the overall trend unresolved and creating large uncertainty in the extrapolation.

Given these limitations, we believe the combined risk is best captured within a statistical envelope (e.g., upper quartile or 95% confidence interval) based on both the parametric and model uncertainties, as illustrated by the dashed red line in Fig. 6. The confidence criteria (e.g., 95% vs 75%) can be adjusted based on overall risk exposure and tolerance, but simply using the median is insufficient as it ignores a 50% chance that the risk is higher than that and removes important information contained in the shape of the distribution (e.g., significant probability contained in the tails). Given the current lack of quantitative characterization of the extrapolated risk uncertainty from our current knowledge base, safety margins needed in mission planning would largely be arbitrary (and could easily be inadequate) as the confidence intervals remain unknown.

Fig. 6 illustrates three regions of particular interest:

A. A “status quo” long-duration mission (>2 years) with current ISS-based countermeasures,
B. A short-duration “fast transit” scenario with current ISS-based countermeasures (<1 year)
C. A long-duration mission (>2 years) with more complete mitigation of the three hazards using novel countermeasures designed and validated for longer (>1 year) duration, deep-space missions.

The current Mars Design Reference Mission durations are in a region of the trade-space with a large integrated risk (Region A). While there are promising technical avenues on the horizon, like AG, artificial intelligence, and advanced shielding, that could potentially bend the curve significantly downward (Region C), there is an enormous amount of research and development necessary before these promises can become reliable realities. Furthermore, the necessarily long-duration validation studies for a 2–3 year mission would generate a significant delay before such missions could be safely accomplished with a reasonable expectation of success. That said, a fast transit’s significantly shorter mission would bring the risk closer to the current acceptable risk regime for ISS (Region B), although reducing the HSIA risk would still require novel countermeasures.

While laden with uncertainty, this first attempt to characterize the integrated safety, health, and performance risks to crew on long-duration expeditions provides insight into the critical decisions and trade-offs that are needed in Mars mission architecture planning. It also

Fig. 5. Notional Variables that exert Influence on Ability of Earth-independent Crew to Resolve Anomalies, with the Expected Influence Curves [1].

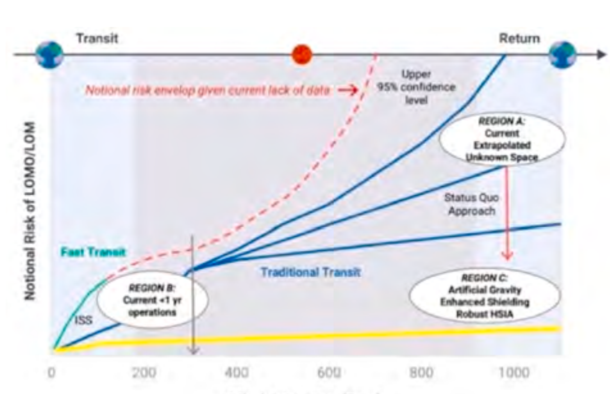

Fig. 6. Qualitative notional integrated mission risk associated with the combination of the three described risk areas.

illustrates current knowledge gaps that need to be filled to support evidence-based extrapolation of spaceflight experience to date to new BLEO regimes. In the case of the radiation and microgravity risks, we do not fully understand the extent of the extrapolated hazards on human performance and, in the case of HSIA, while the hazard is largely understood from decades of experience with the ISS, our knowledge of the nature or effectiveness of potential Earth-autonomous operational solutions remains in its infancy. To avoid simply accepting the uncertainties of Fig. 6 and guessing at what margins must be applied to mitigate them, more research and development targeted towards better characterization and mitigation of the risk is needed.

5. Engineering solutions

As illustrated by the analysis in Section 4, fast transit would achieve a significant reduction in the risk associated with radiation and microgravity exposure because of the significantly decreased overall exposure time. Alternatively, these risks can be reduced by technology investments that enable artificial gravity (AG) and improved radiation shielding. However, because it is a function of distance from Earth, not mission duration, the HSIA risk is not alleviated by fast transit. Therefore, a radical shift in the operational paradigm, systems design, and HSI approaches to support Earth-independent crew decision-making and anomaly resolution will be critical to making the overall risk posture acceptable regardless of the Mars mission duration. Additionally, fast transit architecture and AG solutions continue to face engineering hurdles, and their implementation may increase system complexity that can ultimately increase HSIA risk.

5.1. An innovative flight dynamics approach for a fast mars transit

Given the integrated risk assessment above, we performed a feasibility study of two types of Fast Mars Transits (FMTs):

- A short overall roundtrip mission duration (≤400 days). This is referenced as mission type 1 throughout the paper.
- A short amount of astronaut time spent specifically in deep space (i.e., not on the surface of Earth or Mars). This is referenced as mission type 2 throughout the paper.

For mission type 1, a 400-day roundtrip is significantly shorter than typically proposed crewed Mars missions, which often require astronauts to spend 700+ days away from Earth. In mission type 2, the overall roundtrip mission duration is allowed to exceed 400 days, which can allow for the combined Earth-to-Mars and Mars-to-Earth transit times to be less than the corresponding transit times for mission type 1. There are two primary motivations for examining mission type 2 in addition to mission type 1. First, some of the most significant deleterious health effects, such as radiation exposure and microgravity exposure, accumulate less rapidly when an astronaut is on the surface of Mars than when they are in deep space. The second motivation is that longer Mars stay times allow time for Earth and Mars to naturally move into more favorable positions for the return trip back to Earth, which can significantly reduce fuel requirements for the mission (as discussed below and shown in Fig. 9). A summary of the advantages and disadvantages of minimizing crew time spent in deep space as compared to minimizing overall roundtrip mission duration is presented in Table 1.

In addition to benefits outlined in the previous section, FMT enables sustainable deployment of humans and infrastructure to Mars on a regular cadence, allowing steady exploration and colonization of Mars. The feasibility study performed uses an innovative flight dynamics approach to quantify the minimum total mission Δv required for FMTs of types 1 and 2. For this study, NASA GSFC's software tool Evolutionary Mission Trajectory Generator (EMTG) was used for trajectory optimization, with the objective of minimizing end-to-end mission Δv. For additional details of the study, we refer the reader to Refs. [1,11].

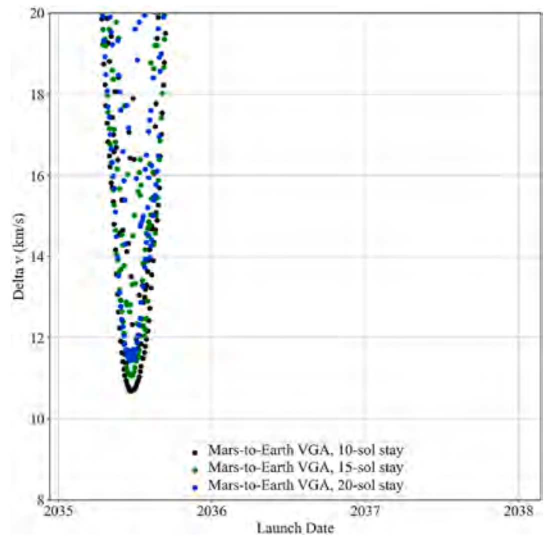

Fig. 7. Δv as a function of launch date for 2.5-sol Mars parking orbit, with VGA, for Mission Type 1: 400-day roundtrip.

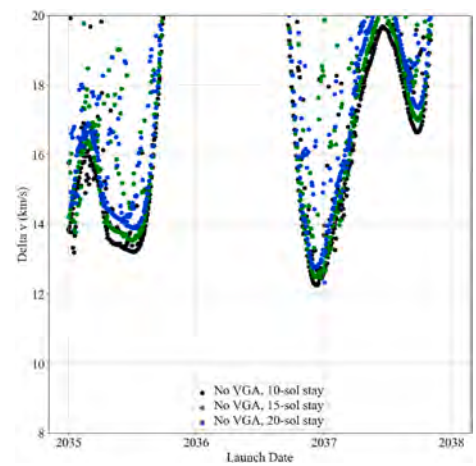

Fig. 8. Δv as a function of launch date for 2.5-sol Mars parking orbit, without VGA, for Mission Type 1: 400-day roundtrip.

Table 2 shows trade parameters considered for mission type 1, and Table 3 shows trade parameters considered for mission type 2.

Figs. 7 and 8 show Δv as a function of launch date with Venus Gravity Assist (VGA) and without VGA, respectively, for mission type 1. The overall lowest Δv cases for the combinations of trade parameters studied are found for the Mars-to-Earth with VGA case for the launch period during June/July 2035. Increasing the Mars orbit stay times from 10 to 20 sols increases the Δv requirement. The "penalty" for increasing the stay time by 5 sols varies but is on the order of several hundred m/s. As expected, a shorter Mars parking orbit period (2.5 sols vs. 5 sols) increases the Δv requirement, also by several hundred m/s.

Fig. 9 shows Δv as a function of interplanetary cruise duration and Mars stay time duration for mission type 2. The minimum Δv's for mission type 2 are significantly smaller than those for mission type 1 because the crew is allowed to "wait" at Mars until the optimal relative geometries are achieved for the return trip to Earth. Such waiting is not possible when the round trip duration is constrained to 400 days.

Mission type 1 likely requires prepositioned propellant depots and staging due to the large Δv required. On the other hand, mission type 2 requires increased prepositioned resources for the crew on Mars (e.g., food and habitats) due to the long Mars stay time. In either case, future work is needed to demonstrate that such Δv's are viable and to

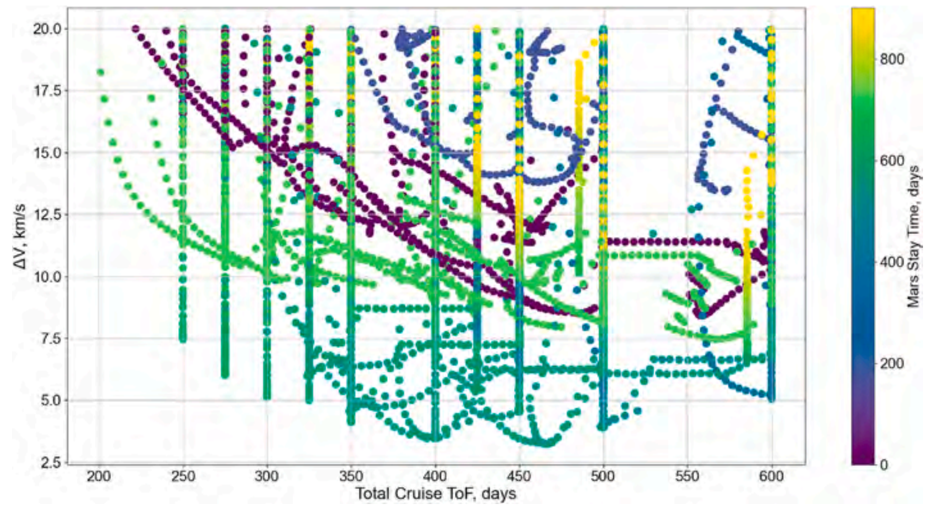

Fig. 9. Minimum Δv trade study results for Mission Type 2: longer Mars stay times.

Table 1
Potential advantages and disadvantages of minimizing crew time in deep space while increasing time spent at Mars (mission type 2).

Advantage	Disadvantage
Shorter time in microgravity	Longer total mission durations
More time available for in situ study of Mars	More resources required at Mars
Fewer resources required in transit	Increased reliability/maintenance requirements on assets at Mars
Lower total Δv requirement for crew's trajectory to/from Mars	Increased multiple health risk due to longer mission duration
Longer time at Mars allows for increased mission schedule flexibility and margin for activities at Mars	

Table 2
Trade parameters for a ≤400-day roundtrip mission to Mars (mission type 1).

Trade parameter	Value(s)
Launch date	Jan. 1, 2035–Dec. 31, 2037
Mars orbit period (sols)	2.5,5
Time in Mars orbit (sols)	10,15,20
Total mission duration (days)	≤ 400
Earth-to-Mars flight time (days)	≤ 60, ≤ 90,≤ 120,unconstrained
Gravity assists	None or VGA during Mars-to-Earth journey

Table 3
Trade parameters for Mission Type 2: longer Mars stay times.

Trade parameter	Value(s)
Launch date	Jan. 1, 2035–Feb. 28, 2037
Mars orbit period (sols)	5
Earth-to-Mars ToF (days)	0-125, 125–150, 150–200,200-300
Mars Stay Time (days)	0-180,180–360,360-540,540–720,720-900
Mars-to-Earth ToF (days)	0-125, 125–150, 150–200,200-300

determine whether such a fast Mars transit is possible without the use of advanced propulsion technologies (such as nuclear thermal or electric propulsion). For example, a key next step in developing mission type 1 is to estimate the amount of propellent required and identify a feasible staging plan to accommodate it. A key next step for mission type 2 is to assess the amount of crew resources required at Mars and the feasibility of positioning these resources at Mars prior to crew arrival. Nevertheless, the results of this feasibility study show promise for sending humans to Mars and returning them safely with acceptable exposure to microgravity and minimal exposure to radiation using current or near-term technology.

5.2. A new paradigm for human-systems integration architecture (HSIA)

One can think of the components that make up this integrated capability — including the crew, the engineered systems supporting the mission, human experts on the ground, data systems, screens, communication devices, and physical spaces—as being a *human-systems integration architecture* (HSIA). An HSIA is the instantiation of communication, coordination, and collaboration between humans and systems that enables execution of complex operations and resolution of safety-critical issues. Whether threats to crew health or vehicle health, this integrated human-systems capability to resolve such issues will be a determining factor in mission outcomes. The challenge then is how to engineer the future HSIA to marshal the required expertise, data, and computation for the small flight crew (approximately four people) to perform the job that has traditionally been done by a much larger and well-equipped ground crew. This will require a fundamental rethinking of crew-vehicle integration, on-board problem-solving and decision-making, and crew-ground asynchronous collaboration.

As seen in historical data, anomalies will occur throughout the duration of a mission, even with the best engineering processes in place. For example, ISS experienced 67 high-priority anomalies from 2001 to 2019. 33 (1.7/year) of these anomalies were vehicle subsystem incidents that required urgent diagnosis [1]; during the "burn-in" phase of ISS (i.e., the first 6 years), the average number of anomalies requiring urgent diagnosis per year was even higher (~3–4 per year) (see Fig. 10).

The historical ISS failure rate is the trend for significant, *unanticipated* anomalies—those that are unknown or even unknowable prior to operations. While it is possible to reduce anomaly rates through improved reliability analysis and testing, and anomaly impacts though added robustness, such mitigations address only known failure modes and known uncertainties. To address the risk of *unanticipated* anomalies

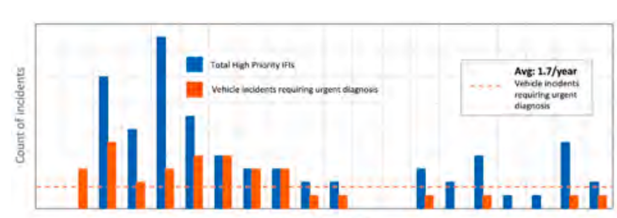

Fig. 10. High-priority anomalies for ISS (red bars show highest priority items requiring urgent response, and blue bars show total high priority items for investigation (IFIs) that were of unknown initial urgency). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

requires increasing *resilience,* the adaptive capacity and extensibility of the integrated human-system to respond to surprises.

Increasing the resilience of the on-board crew—in essence, helping a small crew achieve the same results as 80+ system experts on the ground—will require new technologies and their integration into the crew-vehicle system. Advanced technologies and new approaches will be needed to support situation awareness, hypothesis generation, testing hypotheses against symptoms and other data, and safely deviating from practiced responses, if necessary, all while staying synchronized with the ground team. Needed capabilities may include but are not limited to:

- Artificial Intelligence (AI) to aid the crew in data monitoring, analysis, and trend identification for vehicle systems.
- Advanced sensors and sensor fusion to support crew diagnosis and repair of vehicle systems.
- Virtual/augmented reality for crew execution support.
- Data integration, data architecture, and data visualization to support crew vehicle diagnostic processes and problem solving
- Development of simulation capabilities, including simulated communication delays and crew autonomy during lunar missions, for determining requirements and validating concepts for Earth-independent crew anomaly resolution and complex operation execution
- Advanced maintainability standards and sparing approaches (e.g., additive manufacturing) that support crew in both routine operations and conditions requiring critical repairs.

To radically change human-systems capabilities to address the risks associated with reduced ground support, solutions must be developed at an architectural level. As depicted in Fig. 11, needed functions and their overarching architectural elements and requirements fundamentally rely on each other. Appropriate *communication* of meaningful content (through interfaces) supports *coordination* (interaction) between crew actions and system function, which ultimately enables *collaboration* (integration) among crew and onboard systems to affect higher level goals. For example, to aid the crew in anomaly resolution, the HSIA must support problem solving (e.g., collaboration), procedure execution (e.g., coordination) and telemetry visualization (e.g., communication). Systems engineering processes must ensure that capabilities for all three architectural elements—interfaces, interaction, and integration—are in place to enable high-criticality mission functions.

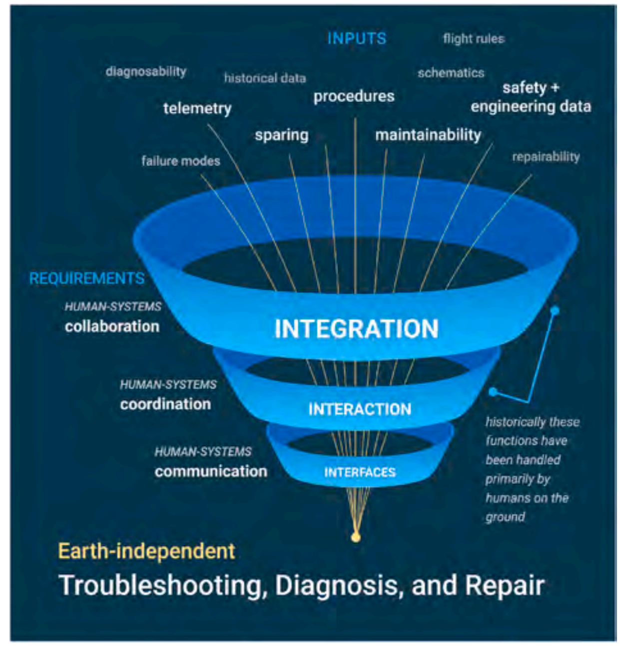

Fig. 11. Elements of a human-systems integration architecture for safe human missions to Mars.

6. Conclusions

In summary, as distance from Earth increases, the safety net of ground support will degrade and be maximally compromised at the moment of greatest need (upon arrival and landing on Mars and during crew surface activities). At the same time, crew capability will also steadily decrease over time due to cumulative degradation of physiological and psychological function from a wide array of spaceflight hazards. This can lead to a decreased ability to perform tasks necessary for mission success and, in the worst case, negatively impact both the health and safety of the crew during the mission and/or their long-term health after the mission is over.

Safe human expeditions to Mars will depend on the integrated capability of the human-system team to keep the crew and the vehicle alive while completing mission objectives. The engineering implementation for exploration beyond LEO must protect the crew's health, support their performance, and accommodate their needs throughout the mission. Fast-transit solutions have the potential to alleviate the effects of radiation and microgravity and reduce the number of anomalies the systems may experience simply by limiting exposure to these hazards. Fast-transit solutions however also have increased potential for unanticipated adverse consequences as they will be novel and complex, thus likely increase the HSIA risk by complicating any autonomous handling of anomalies.

It is also currently unclear how well crew capability can be maintained in a Mars mission after extended exposure to microgravity, but, in many categories, performance in any current Mars Design Reference Mission scenario will degrade beyond our historical experience. If full AG is not provided as an overarching countermeasure by eliminating this hazard (which would also add to system complexity and thus could increase the HSIA risk), significant research will be necessary to characterize the extended effects of this hazard with sufficient completeness to develop and validate effective countermeasures for any mission lasting longer than about a year.

Regardless of breakthroughs in fast Mars transit, radiation monitoring/shielding, or microgravity countermeasures, the challenges that emerge from communication delay and resupply constraints demand a radical paradigm shift in current crewed spaceflight HSIA. Supporting and amplifying the capabilities of small crews to problem solve and manage complex operations autonomously will be vital to the success of future, Earth-independent missions. Hence, there is an urgent need to address on Earth-autonomous human-systems integration and to develop/validate the future architectures that will enable it.

A final overall recommendation from this assessment is that the engineering and medical technical authorities should partner to further refine and explore the integrated human risk trade-space to prioritize research and investment into potential game-changing technologies to significantly reduce risk for an initial Mars mission. There is no escaping the conclusion that the principled design and validation of any such systems with evidence-based safety margins will depend on a systematic effort to fully characterize the hazards and challenges of extended, largely Earth-autonomous, deep-space missions and cannot simply rely on extrapolated estimation using our current knowledge and experience.

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.

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