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Technical Note

Managing Human Inhabitation on the International Space Station: Balancing Environmental Factors and Crew Well-Being

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ABSTRACT

The International Space Station (ISS) presents a complex array of environmental, psychological, social, and technological stressors that challenge human adaptation in orbit. While many of these factors are well documented, this technical note advances a framework of integrated counter-measures tailored to crew size, mission phase, and system contingencies. Drawing from a synthesis of empirical and operational literature, it proposes a layered mitigation model uniting architec-tural, behavioural, physiological, and automation-based strategies. This multidimensional ap-proach supports adaptive trade-offs between habitat constraints, crew autonomy, and mission control support, promoting sustained performance, safety, and psychosocial resilience in extreme environments. The analysis examines implications for expanding occupant capacity, sustaining extended-duration missions, and informing evidence-based design principles for future orbital and planetary habitats. Findings suggest that, under current operational and environmental lim-itations, an ISS crew size of six remains optimal; exceeding this threshold demands rigorous, system-wide application of integrated countermeasures. The paper concludes with targeted recommendations, interdisciplinary insights, and open research priorities to guide the evolution of human factors engineering, digital health integration, and adaptive mission design in next-generation space habitats and long-duration exploration missions.

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NOMENCLATURE

ESA	European Space Agency
ISS	the International Space Station
EUE	Extreme and Unusual Environment
GLCS	Gravity Loading Countermeasure Skinsuit
ARED	Advanced Resistive Exercise Device
VR	Virtual Reality

1. INTRODUCTION

The International Space Station (ISS) is a large, permanently orbiting spacecraft that serves as a base for international crews of astronauts and cosmonauts to live and work in space. The station's unique environment exposes human inhabitants to multiple extreme and unusual environmental, psychological, social, and technological challenges, collectively defining it as an Extreme and Unusual Environment (EUE) [1]. EUEs are characterised by extraordinary physical and psychosocial demands that require deliberate strategies to maintain adaptation, performance, and well-being [1].

Human performance on the ISS is influenced by a combination of physical stressors, in-cluding prolonged microgravity, rapid light-dark cycles, physical confinement, and the inherent risks of space travel. Continuous exposure to microgravity leads to cardiovascu-lar deconditioning, bone loss, muscle atrophy, vestibular disturbances, and sleep disrup-tion [2]. Rapid orbital cycles, sixteen sunrises and sunsets every 24 hours, further disrupt circadian rhythms and contribute to fatigue, cognitive impairment, and mood variability [3]. In addition, confined living quarters and limited habitable space require six crew members to share six sleeping compartments, two bathrooms, and work areas over mis-sions typically lasting six months to a year [4]. These factors, coupled with reliance on technology for life support, environmental regulation, and communications, create a complex set of interdependent stressors that can compromise both physiological and psychological functioning if not adequately mitigated [5].

Despite extensive research documenting individual stressors, a key gap persists: few studies have examined the integrated effects of environmental, psychological, social, and technological challenges on overall crew performance, particularly under varying mission phases, crew sizes, or system contingencies in the space environment. Moreover, while individual countermeasures exist, there is limited guidance on coordinating these strate-gies to optimise performance in real-time operational contexts.

This technical note addresses this gap by proposing a layered mitigation framework that integrates architectural, behavioural, and technological strategies. The framework is tai-lored to crew size, mission phase, and habitat contingencies, providing actionable guid-ance for current ISS operations and lessons for future long-duration, off-Earth habitats such as lunar bases or Mars-class missions. By synthesising existing empirical and oper-ational literature, this technical note offers a structured approach to maintaining physio-logical, psychological, and operational performance in extreme space environments, highlighting both current best practices and open questions for further investigation.

2. METHODOLOGY

This study employs a retrospective narrative synthesis of publicly available and peer-reviewed literature to evaluate human habitation on the International Space Station (ISS) and related extreme environments. The analysis spans publications from 2001 to 2025, including empirical studies, operational reports, and technical reviews, with an emphasis on evidence directly relevant to physiological, psychological, social, and tech-nological stressors in space. Sources included the National Aeronautics and Space Ad-ministration (NASA), European Space Agency (ESA), and peer-reviewed articles from rel-evant industry journals. Interactions between domains were analysed to identify critical dependencies and to develop a layered countermeasure framework. Limitations include reliance on secondary data, variability in reporting standards, and absence of direct hu-man subject experimentation.

3. INTEGRATED ENVIRONMENTAL AND HUMAN SYSTEMS ON THE ISS

3.1 Environmental Stressors

The required spaceflight to travel to and from the ISS has its inherent risks that require

understanding. To get a human from Earth to the ISS, the human body must undergo ap-proximately 3Gs experienced when accelerating during the initial shuttle launch [6], a six-hour flight to reach the ISS orbit, 400 kilometres above Earth's surface [7], and an addi-tional day to allow for ISS docking to precisely occur. Further to this, the risk of trav-el-related death for the space travel population is 3.6%. Far greater than the 0.86% auto-motive travel risk equivalent [8].

Similarly, the ISS remains in orbit around the Earth, travelling at approximately 28,000 kilometres per hour, orbiting the Earth sixteen times in 24 hours. As the ISS follows an or-bital inclination path of 51.6 degrees [9], an obvious lack of permanence in a physical lo-cation for the crew is noted and remains truly unusual when compared to other inhabited environments.

Orbital habitation onboard the ISS presents multiple unique physical stressors. Continu-ous microgravity leads to cardiovascular deconditioning, loss of bone density, muscle at-rophy, and vestibular disturbances [2, 5, 10]. Countermeasures include structured resis-tive and aerobic exercise regimens of at least two hours daily, which mitigate musculo-skeletal degradation but require strict adherence and careful scheduling [11,12]. Techno-logical innovations like the Gravity Loading Countermeasure Skinsuit (GLCS) are re-shaping in-flight countermeasures. By applying tension from the shoulders to the feet, the GLCS mimics gravity's effects, helping reduce spinal elongation, support posture, and maintain cardiovascular tone [5].

Sleep disturbance has been linked to the microgravity aspect of the environment. This condition may be compounded by a shortened circadian rhythm caused by the rapid light-dark cycles. Generally, the human sleep/wake cycle is governed by rhythmic envi-ronmental stimuli as the 24-hour light/dark cycle repeats each solar day [13]. However, unlike the general rule or the polar day/night variant witnessed in their respective regions, the ISS experiences 16 sunrises and sunsets for each 24 hours [4]. On-orbit sleep disturb-ances are very common among astronauts and may have detrimental influences on a crewmember's health or the safety of flight missions [3]. NASA recommends that astro-nauts sleep eight hours per day in orbit [14,15]. This has been supported by a detailed on-orbit work-rest schedule and the improvements in the sleep environment, allowing each crew to have comfortable sleeping bags, restraints to prevent floating, and private sleep quarters to reduce sleep interruptions [15]. This is to minimise the effect of a circa-dian rhythm misalignment that can have severe health ramifications, including the dete-rioration of a crewmember's cognitive, physical and psychological attributes, leading to poor space operation performance and emotional instability [3]. Mitigation strategies such as circadian-aligned lighting, temperature modulation, and environmental zoning have been used to improve sleep quality and operational performance [3].

3.2 Psychological and Social Stressors

The stressors applied by the physical characteristics of the ISS can be exaggerated with the unplanned addition of personnel from a different contributing nation. Although the ISS has historically accommodated nine occupants spanning four days from November 6th to 10th, 2013, the ISS is designed for long-term occupation by a maximum of six astronauts [16]. Mission extension and alterations can result in additional occupants, thus physically confined human inhabitants of the ISS, having to negotiate for personal and working space to coexist. This highlighted a key inadequacy of the ISS, which only supports six sleeping quarters that will need to be shared in a sleeping rotation arrangement. As pre-viously mentioned, due to the unique light/dark cycling, it is crucial that adequate sleep occurs to reduce the deterioration of a crewmember's cognitive, physical and psychologi-cal attributes to prevent poor operation performance and emotional instability [3].

Specifically, the risk of psychological deterioration is of concern as there is already a high perceived consequence for mission failure that may jeopardise the long-term viability of the station and subsequently the nation's space program. Further to this, as time pro-gresses, aroused suspicion may arise that the other team members may be trying to un-dermine or disrupt the work that is being undertaken may occur. These unsupported ac-cusations affirm the point that interpersonal stressors are compounded by EUE character-istics and may result in social conflict [9].

Conflicts, perceived or supported, jeopardise the efficacy and efficiency of self-managing teams, diminish the mission's integrity, and may insight

non-recoverable failure [17]. A potential conflict could arise between Mission Control and the ISS crew if Mission Control were perceived to prioritise one set of tasks over another that the crew deems more critical. If more time were allocated to the less critical tasks, this could highlight a disconnect in priorities between the two teams, instigating an 'us versus them' situation. This subtle conflict regarding the priority of task changes on the ISS can have catastrophic ramifica-tions if it continues. As the habitability of the ISS is reliant on team cohesion and perfor-mance, any conflict may compromise the quality of research, repairs or upgrades, thus al-lowing the ISS to succumb to the extreme dynamics of space.

3.3 Technological Dependence

The survival of ISS crew members depends on advanced technological systems for their existence. The life support systems of the space station maintain oxygen levels and control carbon dioxide and humidity while recycling water and monitoring environmental con-ditions for thermal and atmospheric safety [18,19]. The prevention of catastrophic sys-tem breakdowns depends on both backup system planning and scheduled maintenance operations. The combination of advanced automation with AI-based monitoring systems helps decrease crew mental workload while optimising work assignments, detecting po-tential system problems, environmental changes, and crew fatigue. The combination of telemedicine with virtual reality-based recreational activities and real-time ground control communication systems through virtual reality enhances operational support, which leads to better crew health and performance outcomes [20,21]. Virtual medical avatars represent a promising solution for ongoing health surveillance and post-mission check-ups during extended space missions because traditional medical services become unavailable [21].

4. COUNTERMEASURES AND MANAGEMENT STRATEGIES

Effective management of environmental, psychological, and operational stressors on the International Space Station (ISS) requires a coordinated system of countermeasures rather than isolated interventions. The most resilient strategies are those that integrate architec-tural design, behavioural management, and technological augmentation into a unified operational model that can dynamically adapt to mission conditions and crew composi-tion.

4.1 Architectural and Environmental Interventions

The physical structure of the ISS plays a crucial role in mediating stress and sustaining performance. Architectural countermeasures aim to balance privacy, safety, and collabo-ration within the constraints of limited volume. Compartmentalisation of sleeping quar-ters provides necessary personal space for psychological decompression, while noise-dampening materials and vibration control systems reduce sensory overload. Spa-tial zoning, distinctly separating work, recreation, and rest areas, reduces cognitive fatigue and enhances role delineation, thereby improving operational efficiency.

Environmental modulation through circadian-aligned lighting systems has emerged as a particularly effective tool for mitigating sleep disruption and maintaining cognitive per-formance [3]. Dynamic lighting that adjusts colour temperature and intensity to simulate a 24-hour Earth-like cycle supports hormonal regulation of melatonin and cortisol, there-by improving sleep onset latency and alertness during waking hours. Thermal and hu-midity control further stabilise comfort and reduce irritability. These environmental inter-ventions represent the first layer of human-system integration, directly linking physical habitat design with physiological regulation and psychological well-being.

4.2 Behavioural and Operational Strategies

The main focus of Behavioural countermeasures involves creating structured work sched-ules, managing workloads, and providing psychosocial support to crew members. The core element for maintaining both physical health and mental well-being involves estab-lishing specific work-rest patterns, which include scheduled time for exercise and leisure activities [14]. The Advanced Resistive Exercise Device (ARED) and Treadmill 2 systems help prevent muscle deterioration while offering psychological advantages through estab-lished routines and physical activity.

Crew autonomy in task scheduling has been shown to enhance engagement, intrinsic mo-

tivation, and team cohesion, offsetting the potential demotivation associated with contin-uous oversight from Mission Control. Periodic rotation of tasks reduces monotony and cognitive fatigue, while group debriefings promote shared situational awareness. The combination of psychological resilience training with mindfulness practices and sched-uled family contact helps crew members deal with feelings of isolation and homesickness and interpersonal conflicts [22]. Importantly, these behavioural programs are reinforced by a culture of transparency and psychological safety, enabling early identification of ten-sion or burnout before they manifest as mission-compromising behaviours.

4.3 Automation and Technological Support

The dual nature of technology exists because it serves to protect astronauts while simul-taneously creating additional stress factors. Real-time biosensor monitoring tracks heart rate variability, sleep quality, and cognitive performance to detect early signs of physical or mental deterioration, which enables preventive measures [16]. AI systems now handle these data streams to create predictive models which help optimise crew work distribu-tion and rest periods, and environmental control systems.

Telemedicine systems enable medical specialists on Earth to provide both immediate and delayed consultations to space crew members who operate beyond human medical exper-tise [20,21]. The combination of virtual medical avatars with augmented reality interfac-es enables astronauts to perform diagnostic, therapeutic, and procedural tasks when communication delays occur during missions above low Earth orbit [21-23]. Virtual reality (VR) environments create sensory experiences that help people escape their sur-roundings while providing mental stimulation to combat feelings of isolation and bore-dom. The systems enable emergency training simulations, which help astronauts main-tain their skills and build their confidence and memory of procedures.

The implementation of automation in space operations leads to better safety and reduced workload, but excessive dependence on automated systems can impair both situational awareness and human problem-solving abilities. Therefore, future system design should balance technological augmentation with human oversight, preserving the astronaut's ac-tive role as operator rather than passive monitor.

5. LESSONS FOR FUTURE HABITATION

Experience from Mir, Skylab, and the ISS demonstrates that sustainable habitation in deep space depends on dynamic integration of environmental, behavioural, and technological systems. Future lunar and Martian habitats need to function as independent life systems that maintain both engineering stability and psychological strength. The study of ana-logue environments shows that habitat design needs modular structures with redundant life support systems and adjustable lighting and spatial areas to preserve mental function and social unity in extended space missions [24,25]. Digital well-being technologies with privacy-focused interfaces that support autonomy and trust function as stress-reducing tools for interpersonal stability during extended space missions, according to behavioural health research [23,26].

The necessity for autonomous medical and operational choices becomes essential when communication becomes delayed and supply delivery becomes restricted. NASA medical bay design concepts and clinical decision-support frameworks use AI diagnostics and augmented reality training, and virtual reality to create countermeasures for cognitive and emotional health [27]. The technologies need to work alongside human flexibility instead of replacing it because future habitats need ongoing feedback systems that connect archi-tectural elements with human conduct and intelligent system operations. The ISS demon-strates that deep space habitat success depends on creating self-regulating psychological ecosystems that maintain performance and safety through engineering excellence and sustainable design.

6. CONCLUSION AND RECOMMENDATIONS

Sustained human habitation on the ISS demonstrates the necessity of multi-domain management strategies addressing environmental, psychological, social, and technologi-cal stressors. Key recommendations include:

- Maintain six-person occupancy for optimal performance unless rigorous inte-grated management is applied.
- Prioritise integrated monitoring systems linking environmental, physiological, and psychosocial domains.
- Enhance crew autonomy while maintaining structured behavioural and opera-tional support.
- Apply ISS lessons to future long-duration habitats, including autonomous medi-cal and AI-based operational support.

Open questions remain regarding adaptive countermeasures under unforeseen contin-gencies, psychological resilience in ultra-long missions, and scalable habitat design. Fu-ture research should empirically validate integrated frameworks and conduct cross-mission comparative studies to ensure evidence-based planning for off-Earth habi-tation.

CONFLICTS OF INTERESTS

No conflict of interest has been expressed by the authors.

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