Long-Duration Spaceflight Habitability Lessons Learned

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PREFACE

The Long-Duration Spaceflight Habitability Lessons Learned, was prepared by NASA, Johnson Space Center, Flight Operations, Intravehicular Activity.

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1.0 INTRODUCTION

1.1 PURPOSE

This paper documents habitability design considerations in space vehicles used for long-duration missions (≥ 30 days). The lessons learned are from decades of support to the crew of the International Space Station (ISS) by NASA's Intravehicular Activity (IVA) branch. By following the recommendations in this paper, spacecraft designers can provide vehicles that accommodate the crew needs – in turn enabling the crew to focus on their mission.

Spacecraft design that adequately accommodates habitability – the quality of being suitable for humans to live in – supports the physical and psychological needs of crewmembers. Human spaceflight, while exciting, is dynamic and highly stressful. The body and mind are stretched to their limits, impacting performance. Consequently, managing stress for human spaceflight participants via habitability is not only a matter of comfort, but ensures crew safety and ultimately mission success.

Crewmembers have basic human functions that must be accommodated during a mission, such as eating, drinking, sleeping, and going to the bathroom. The easier it is for crewmembers to meet these needs, the more they can effectively focus on technical tasks and mission objectives. While it is possible that crewmembers can tolerate less-than ideal habitability facilities for short-duration missions, inadequate provisions are undesirable and are possibly intolerable – especially during long-duration missions. While crew are adaptable, it is far preferable to ensure facilities are consistently adequate and available. Doing so will ensure crewmembers do not need to spend precious time adapting or developing alternative ways to have their basic needs met.

Habitability is important in any space vehicle, but it is vital in space vehicles where crew will live and work for long-duration missions. Two examples from the ISS highlight that what was acceptable on the Space Shuttle (short-term missions) was not necessarily acceptable on ISS (long-term missions). In the Galley and hygiene facility examples detailed below, the habitability facilities for the ISS were similar to those for the Space Shuttle – neither vehicle had a dedicated table or hygiene area. The crew accepted the lack of facilities on the Shuttle, but on the ISS, they created their own workarounds to address the lack of adequate design. Both of the improvised solutions on board the ISS caused concerns that necessitated ground response in the form of real-time mission support, hardware configuration analyses, remediation efforts, and new design solutions.

Galley Table

There was originally no dining table on the US side of the ISS. Planners assumed that crew would place food items and utensils wherever it was convenient, or that they would use the table in the Russian segment. After a few increments, though, crewmembers scavenged an unused portion of the Russian table and installed it in the US segment. The new table aided in food preparation and consumption and provided a place for the crew to gather. Eventually, NASA provided a Galley Table to replace the bespoke one created by crewmembers. Since then, crewmembers have consistently emphasized how important that table and gathering place were to morale.

When the crew installed their own table, it exposed a need for an overall Galley space on the US segment of the ISS. A rack to enable co-location of all Galley hardware was eventually designed, launched, and installed in the Node 1 module, but Node 1 was not initially designed to be a Galley space. Consequently, the Galley Table infringed on the egress path, so the crew could not leave it untended in its fully deployed configuration. Additionally, there were hardware concerns with food and beverage release, which is unavoidable in microgravity. The nearby hatch seals had to be inspected and cleaned more frequently than the hatch seals in other modules. Nearby rack faces were also replaced since they were not initially built with readily cleanable materials (see *Galley* Section, Figure 4-1).

Hygiene Location

The ISS did not originally have a dedicated place for crew to bathe, shave, wash their hair, etc. The plan was for the crew to use the enclosed toilet volume for hygiene because it was designed to have good airflow and protection from fluid release. However, the toilet area was in high demand. Anyone using it for hygiene made it unavailable for someone needing the toilet and vice versa. Additionally, crewmembers strongly disliked doing hygiene so close to the toilet.

Crew initially created an alternative hygiene space in one of the Russian modules, but this led to mold growth on the carpeted module walls. Crew then moved hygiene into the stowage module. They repurposed some old blackout curtains as a privacy barrier, which also later tested positive for high levels of microbes. Due to the crew's efforts, the ground recognized that the crew needed a separate hygiene location and the stowage module seemed to be the best solution within the existing volume of the ISS. There, crew could spend more time doing hygiene in an area that provided privacy and would not be urgently needed by other crewmembers.

The hygiene space in the stowage module was inspected and disinfected regularly. Additionally, ground teams created hydrophobic hygiene curtains to provide privacy and protect stowage from water. Because the stowage module was never intended to be used as a habitability module, the module lighting and airflow were not ideal for a location where crew spent significant time. Additionally, there were stowage impacts to reserving part of this module for hygiene. Some of the space originally designated for stowage could no longer be used as such. Crew had to plan their hygiene activities around stowage operations, especially during visiting vehicle loading and unloading. Finally, any hardware incompatible with water and hygiene products had to be stowed in a separate location.

In both Galley Table and hygiene location instances, crew improvised solutions to make existing facilities more habitable, which highlighted a need for long-term habitability solutions. Many of the issues addressed could have been avoided if dedicated spaces had been provided. Significant time and resources were spent to come up with long-term solutions in spaces not designed to support those functions. Planning ahead for habitability early in the design process will minimize expensive, sub-optimal, and time-consuming efforts to retrofit solutions and allow for optimized accommodations. This document provides guidance on key habitability design considerations for the benefit of long-duration human spaceflight.

1.2 SCOPE

Two criteria apply to the scope of this paper:

1. The habitability concepts addressed in this paper apply to space vehicles that will house crew in microgravity for long-duration missions (≥ 30 days).

   As our space travel capabilities evolve from lower earth orbit to the moon and Mars, different types of vehicles become part of the fleet. Vehicles used for short-duration crew transit or as surface vehicles are not the focus of this paper. While many of the overarching habitability principles will still apply, not all the specifics will. For example, crewmembers may not require a private crew compartment for short-duration missions. Similarly, restraints and mobility aids will likely look very different in a surface vehicle where gravity is a factor.

2. The topics chosen for this paper are those where the IVA discipline is a subject matter expert and/or hardware operator.

   (a) The IVA group manages stowage, maintenance, and most habitability hardware on the ISS. This paper focuses on lessons learned because the IVA console has worked with crewmembers throughout the ISS program. Other disciplines also own and operate hardware that is applicable to habitability. This includes, but is not limited to, crew clothing, crew personal items, food and beverages, radiation, and exercise. We have chosen not to include these topics as they are outside the purview of the IVA discipline.

   (b) There are two exceptions to this part of the scope definition. In the *General Habitability* Section, we briefly address CO2 scrubbing and windows. Neither are fully owned or operated by the IVA group. However, these two topics have been cited by previously flown crewmembers as vital to habitability. This paper documents what is most important about these two topics from a habitability perspective and includes additional references to more technical information.

2.0 SLEEP AND PRIVACY

2.1 OVERVIEW AND PHILOSOPHY

Crewmembers spent up to a third of their long-duration space mission sleeping. Quality sleep is vital to a human's health, mood, and productivity. Fatigue and lack of privacy while working in close quarters negatively impacted the crew's physical wellbeing and their mood, and therefore could have impacted mission success. Investing in smart sleep station design that supports crew physical health and provides privacy and solitude helps ensure a safe and productive mission.

This section focuses primarily on lessons learned from the ISS Crew Quarters. The terms "sleep station" and "crew compartment" will refer to a general concept, and "Crew Quarters" will refer to the specific ISS Crew Quarters design. Note that on the ISS, crewmembers did more than just sleep in their Crew Quarters; they may have worked on their laptops, conducted private conferences with loved ones and physicians, listened to music, watched movies, relaxed, etc. Crewmembers widely expressed a preference that their sleep stations accommodate a private multipurpose personal space as well as sleep.

2.1.1 Sleep Quality

Crew Quarters supported crew physical health by providing conditions for quality sleep. A significant amount of research has explored what constitutes good sleep quality. Experts agree that a consistent schedule promotes falling asleep quickly and staying asleep. Additionally, sleeping in a quiet, dark, and clean environment with a comfortable temperature and bedding encourages quality rest. These basic factors apply almost universally from person to person; however, individuals have specific preferences. Consequently, features such as flexibility with temperature control in system design are highly desirable.

2.1.2 Privacy

Privacy was a vital function of a sleep station. In the close quarters of a space vehicle, especially during a long-duration mission, privacy allowed individual crew to retreat, relax, and recharge. In this case, a private space had the ability to be closed off and isolated from the general cabin, with material that aided in noise attenuation and secured in the closed position. Solitude had a regulatory effect on the crew and contributed to overall decreased stress levels. Additionally, the crew compartment was typically a crewmember's only personal space on board, with full autonomy in the modularity of this volume and the ability to personalize it. Living in and knowing that they had a private space was beneficial to mental and emotional health, which contributed to a crew's dynamic.

In addition to a physical retreat, a sleep station must also have auditory isolation to be considered truly private. Auditory isolation allowed crew to have private conversations with loved ones, their flight surgeon, and ground teams. It also allowed for crew to watch movies, write emails, and do other activities in their private area without disturbing their fellow crew.

2.2 HARDWARE CONSIDERATIONS

The unique use of sleep stations made them different from other habitability hardware. Sleep stations were some of the only hardware that saw daily, continuous crew use for 8-9 hours. It is also likely sleep stations were the only hardware that had a singular user for the entirety of a mission, which were then repurposed for a different crewmember upon completion. The following sections will focus on the hardware considerations unique to sleep stations.

2.2.1 Location of Sleep Compartments

Sleep compartments should be located away from high-traffic translation paths because these areas are generally quite noisy. Sleep compartments should also be placed away from toilet and exercise areas to mitigate odor and cleanliness concerns. Additionally, sleep compartments should be located away from the Galley, which was a common place the crew gathered and socialized. Late night and early morning conversations and meals would wake up a nearby sleeping crewmember, both in terms of noise and food smells. Furthermore, food particulate contributed to onboard “dust,” and locating a crew compartment away from the Galley would help mitigate foreign object debris (FOD) buildup.

Crew Quarters were collocated on board the ISS. The disadvantage of the close proximity was that CO2 generation concentrated to one area during peak occupancy. Ventilation and CO2 removal systems must be designed to effectively remove the CO2 from the sleep area(s). Some ISS crewmembers suggested that separating the sleep stations could be beneficial because it would provide further privacy and support a quieter environment. Conversely, other ISS crewmembers reported that close proximity sleep stations promoted good crew morale and other social benefits. Namely, a cohesive crew appreciated being together and collocation is convenient in case of an emergency, allowing for crewmembers to quickly wake and notify one another. Considering both viewpoints, high importance should be placed on designing sleep stations with exemplary auditory isolation so that crew can enjoy the benefits of close proximity while maintaining privacy as desired.

2.2.2 Size

The ideal sizing for sleep compartments is generally dependent on the tasks that the compartments are intended to accommodate. Crewmembers widely agreed that they preferred their sleep station to accommodate other activities in addition to sleep, including working on a laptop, private conferences, and personal relaxation such as reading and watching movies. At a minimum, the sleep compartments should have enough space for crewmembers to ingress, climb inside a sleeping bag, and adjust their sleeping position comfortably. In April of 2000, the Johnson Space Center (JSC)

Astronaut Office recommended that sleep stations be sized such that a 95th percentile male can change clothes inside.

Another sizing consideration is that crewmembers will have personal items to stow conveniently and privately throughout their mission. This could include clothing, personal items (e.g., books, family mementos), hygiene items, headphones, etc. Crew have indicated a preference to stow at least some of these items inside or near their sleep compartment. Additional volume allocated within the Crew Quarters could accommodate this stowage. Alternately, space outside/near the sleep compartments could be allotted for personal stowage.

2.2.3 Cleanability

The Crew Quarters accumulated FOD over time. During their time on board, crew shed skin and hair, and sweated (contributing to moisture and microbial growth on surfaces). This debris built up mostly in their sleep compartment because of how much time they spent there, but also because bedding tended to rub against skin when getting settled or readjusting during sleep, which contributed to sloughing. After about 3-6 weeks in microgravity, the callouses that developed from time spent on one's feet on Earth sloughed off due to disuse. During this time, there was a significant amount of dead skin liberated. If a mission is three weeks or longer, it is recommended for crew to perform additional cleanings during and after the adjustment period based on their preference and medical needs.

To account for FOD buildup, it was critical to consider how it would impact the airflow system. Even with regular cleaning and fine-mesh screens, FOD tended to make its way into the airflow system. FOD degraded hardware over time, and dead skin was particularly challenging to clean out of ducting. Due to dust buildup within Crew Quarters' ducting on ISS, airflow system deep cleaning was instituted between missions. It is recommended that any sleep station design enable easy access to vents and interior ducting for cleaning as needed.

Over the course of ISS, some crews elected to eat, drink, and perform hygiene tasks in their Crew Quarters, which over time led to a buildup of various kinds of FOD and stains on the hardware. The ISS Program chose to protect the Crew Quarters' wall blankets with replaceable covers. In general, refraining from eating and performing hygiene ops in a sleep station was the best way to ensure it remained clean, both over the course of a mission and a longer campaign. However, if crewmembers were not given a comfortable alternative location for these tasks, they did use their Crew Quarters. Providing a dedicated, functional, and comfortable place for hygiene and eating was the best way to ensure the crew did not have to eat or conduct hygiene in their sleep stations. Further design considerations for these areas will be discussed in the *Galley* Section of this paper.

Regardless, if crew decide to perform alternative activities in their sleep compartments that may adhere to surfaces, it is recommended to design sleep station surfaces with easy to clean and disinfect materials that do not absorb liquids.

2.2.4 Crew Restraints

Historically, the primary restraint used in a crew compartment was a sleeping bag that could be attached to structure. If sleeping bags are used for longer than three months, they should be cleanable or have a changeable liner; if not, spares must be provided. Additionally, the design of the bag should accommodate sleeping in both an extended position and with knees folded to chest. Most crewmembers experienced back pain at the beginning of their mission as their body adjusted to microgravity, and sleeping with knees bent to chest helped alleviate their pain.

In addition to attachment points for the sleeping bag, alternative attachment points should also be provided for a variety of needs. To simulate the feeling of a “blanket” or of “sleeping on your back,” crew restrained their body in the sleeping bags to a wall. Many crewmembers also preferred to secure their feet towards the “bottom” of their sleep station, creating a need for a handrail or bungee that could be padded (if desired) for comfort. This padded handrail also supported activities other than sleep, such as working on a laptop. Restraints to accommodate this can be considered in the overall sleep compartment design.

2.2.5 Stowage Accommodations for Personal Items

Additionally, since crew used their sleep compartment for other personal activities, there should be internal stowage accommodations for personal items. Items that were stowed within the sleep compartment included laptops, photos of family, easily accessible recreational items such as books, and personal items needed for sleep such as ear protection and eyewear. For sleep related items, it is advisable for stowage solutions to be within reach of a crewmember while in their sleeping bag and designed specifically to retain items in microgravity. Additionally, crew commented that stowage solutions with a unique shape or texture would help them identify items by touch in a darkened compartment. In general, providing a variety of attachment points for personalization helps account for individual preferences.

2.2.6 Air Flow

Air flow was one of the most important considerations when designing the Crew Quarters. The Astronaut Office required controllable ventilation (direction and flow rate) for sleep stations that NASA Astronauts occupied. However, it was critical that crew control of ventilation be limited to airflow direction and fan speed that met the minimum requirements for CO2 removal. Portable fan use was leveraged extensively in the ISS Crew Quarters to provide the desired air flow beyond the built-in ventilation. Portable fans were secured in a variety of locations to allow for a customized airflow pattern to fit the needs of each crewmember’s physical comfort. The ISS Crew Quarters design did not allow for personalized temperature settings; however, adjustable temperature was a highly desirable feature for optimum sleep quality and should be prioritized in sleep station design.

Because airflow was so critical in a sleep compartment, some sort of redundancy in the system was necessary, including integration with the Caution & Warning system to alert crewmembers to a reduction of airflow.

Materials used to direct airflow will change with time. Foam in the Crew Quarters ducting broke down over time and was believed to have disrupted airflow enough to result in discomfort and even headaches and sinus issues. For future designs, using durable, easily cleanable materials that stand up to airflow, and designing components that can be replaced, will ensure that a sleep station design can continue to safely house crew for multiple missions.

2.2.7 Caution and Warning

Although it was important that a sleep station provided a quiet environment to support quality crew sleep, it was also important that a crewmember had awareness of any event requiring immediate crew action. This class of event was one that could have jeopardized crew safety or the mission entirely. Some form of Caution & Warning system is standard on any crewed spacecraft, but it had to take into account that, during sleep, crew would be in a dark, acoustically isolated space with decreased cabin lighting, and would likely be somewhat disoriented if startled awake. On board the ISS, this was accounted for with Caution & Warning speakers inside the Crew Quarters that annunciated tones, and LEDs that indicated the egress direction.

2.2.8 Quiet

Quality sleep requires a quiet environment. Powered equipment, flight computers, and various payloads on board a spacecraft contribute to a noisy environment. Ideally, a sleep station would provide acoustic protection to meet an ambient noise level of NC40 or below. While the ISS Crew Quarters did meet this requirement by having interior and exterior walls covered with acoustic dampening blankets, the metal-on-metal design of the Crew Quarters doors were not considered when assessing the acoustic environment. When these doors are opened or closed in the middle of the night, they produced a sound loud enough to wake up other crewmembers, particularly light sleepers. Acoustic dampening design combined with a cohesive understanding of nearby acoustic sources are both critical to maintaining a quiet sleep station.

2.2.9 Lighting

The lighting conditions on board should also support quality crew sleep. Lighting throughout the mission was artificially created; a dark environment when crewmembers are sleeping ensured they fall asleep quickly and stayed asleep throughout their sleep period. It is important that a sleep station design limits the amount of light pollution from the cabin. Internal sleep station lights promoted optimal crew sleep cycles and comfort by providing variable color tone and brightness settings. Additionally, light positioning should be optimized for the activities being performed, which may require allowing crew to relocate the light as desired for sleep or recreational activities.

An ISS Payload experiment explored a circadian lighting system that changed lighting conditions based on a customized sleep schedule to help promote focus during the day and restful sleep at night. At the time of this paper's writing, the results of the experiment have not been published, but initial reports are promising. This design concept is worth exploring to support better sleep for crew on long-duration missions.

2.2.10 Utilities

Crew compartments should be designed with network access and plug-in capability to charge laptops and other devices. Note that powered hardware generates heat, which impacted comfort inside a sleep station, so any additional heat loads need to be considered.

2.2.11 Radiation Protection

During their time in space, crew were exposed to higher levels of radiation. Designing sleep compartments with radiation protection in addition to shielding throughout the vehicle can help mitigate adverse health effects to crew.

2.3 OPERATIONAL CONSIDERATIONS

A thoughtful hardware design can set the stage for quality sleep, relaxation, and a healthy environment, but how the hardware is operated also significantly impacts crew habitability.

2.3.1 Accessibility

Because the sleep station was used for personal activities throughout the crew's day, crew required access their sleep station at any time. If the sleep station must be collapsed or used for another purpose during the workday (neither of which is ideal if one of the goals is to preserve a personal space for crew), then it should be able to be reconfigured into a sleep station in a minimal amount of time so as not to preclude crew use of the sleep station at their discretion. Additionally, any disruption of the crew compartment air flow due to reconfiguration should be accounted for prior to crew occupancy.

2.3.2 Scheduling

When it comes to sleep, crew has diverged from their planned timeline to achieve the necessary amount of sleep. Although they understand the importance of the mission, crew is more likely to make mission-impacting mistakes when fatigued. When it comes to scheduling sleep, it is recommended for planners to work directly with the crew to understand their individual preferences. An inadequate sleep plan that fails to consider individual habits could result in crew deviation from the plan or errors due to fatigue. All humans have their own optimized bedtime, wake time, and sleep duration, which is generally 7-10 hours per day. Additionally, depending on the quality of sleep, some crewmembers found that they needed additional naps during the day; sleep tendencies on orbit can be drastically different than on Earth.

2.3.2.1 Staggering Sleep

NASA research determined that having crew work the same hours, instead of splitting them into shifts, was ideal because it facilitated camaraderie and cohesion. Unfortunately, this was not always possible. Sometimes crewmembers were required to sleep shift on different timelines than their crewmates. In these cases, an isolated light and sound environment helped support good rest while other crewmembers were still awake and working. However, a working crewmember on a split shift may be incapable of performing all tasks without inadvertently waking sleeping crewmembers.

2.3.2.2 Sleep Shifting

There are generally two methods of sleep shifting: slam shifting and gradual shifting.

In a gradual shift, crewmembers shift their bed/wake times by 1-2 hours over the course of several days. This method was easier to implement if crewmembers were shifting ~4 hours, and became more challenging as that gap increased. The drawbacks to this method are that it required a lot of advanced planning, and crewmembers typically had trouble going to sleep earlier, so they had less and less restful sleep in the days leading up to their shift.

In slam shifting, the crewmember did not change their bedtime and wakes whenever needed, usually resulting in less than the ideal 7-10 hours of sleep at a time. However, after the task was complete, the crewmember usually napped for several hours and then went to bed at the normal time. Some crewmembers preferred this method, especially for shifts on the order of 6-8 hours. The primary drawback is that crew was more likely to experience fatigue during their shift, and it can be challenging to get to sleep at a normal time when combined with a nap earlier in the day.

Every individual and crew were different. Crews should be consulted as to their preference during planning and execution for a mission. The impact of sleep shifting on crewmembers should not be underestimated – it takes on the order of 1-2 days for the human body to adjust their sleep schedule by just one hour.

2.3.3 Maintenance

Crew Quarters required regular preventive maintenance to keep them clean and functional. On board the ISS, crews cleaned their Crew Quarters at least once a week during regular housekeeping, and performed an additional deep clean in preparation for handover to the next crew. Regular housekeeping consisted of vacuuming and wiping down surfaces, while deep cleaning involved taking apart hardware and cleaning behind panels and within the ventilation system.

Earlier in this section, privacy was identified as one of the primary objectives of a sleep station. Part of that privacy was not having others in one’s personal space. When maintenance was required on a Crew Quarter, it was much preferred to have the crewmember staying in that station perform the maintenance. If it cannot be avoided, giving the crewmember advance notice and time to situate their things before maintenance can help preserve privacy. Crewmembers should always be consulted before directing someone to ingress another's "bedroom." Additionally, imagery into a sleep station should be limited to only those pictures and videos necessary to complete the mission. When imagery is required, the occupying crewmember should be given time to remove any personal items to protect their privacy.

2.3.4 Campout

NASA Astronaut Corps requires a personal sleep station for each crewmember on missions lasting 30 days or longer. But what about missions shorter than 30 days, or when the number of crew during a handover exceeds the number of sleep stations? In this case, crew will "camp out" in the cabin. This has involved setting up a sleeping area (typically a sleeping bag secured with restraints and mobility aids, a laptop/tablet, and some personal items) in a designated area of the cabin, then packing it all away after waking to clear a working volume. Crew ideally camped out as short as possible because the open cabin was noisy, bright, and not private. Best practices to improve the experience when possible include crew separation if possible. There have been up to four crewmembers camping out on board the ISS during crew handover. Each crew was usually assigned to sleep in a different module, and they were all positioned relatively out of each other's eyeline to provide as much privacy as possible. Additionally, they were given specific locations to sleep that were evaluated for various safety and comfort factors, including structural support, kick loading to nearby hardware, the radiation environment, airflow, flammability, acoustic limits, egress paths, and proximity to trash. Not all areas on board a spacecraft are safe for a crewmember to sleep, so providing specific locations was critical. To support better sleep quality, crewmembers used eye masks, ear plugs, or headphones to block out light and drown out noise. Lastly, crew were given additional time on their daily plan to pack up and deploy their sleeping arrangement so they did not have to sacrifice any of their personal time.

3.0 HYGIENE

3.1 OVERVIEW AND PHILOSOPHY

Hygiene in space has historically been one of the most challenging aspects of habitability in microgravity. Most hygiene on the Earth's surface is dependent on, if not significantly made easier by, running water. Unfortunately, science and engineering have not figured out how to achieve running water in microgravity.

With this obstacle in mind, hygiene in microgravity is categorized as either wet or dry. Wet hygiene refers to traditional bathing or washing hair; tasks that would require disrobing and using more than about 50 mL of water. Dry hygiene refers to tasks that use less or no water, including brushing teeth, shaving, cutting hair, clipping nails, etc. Typically, wet hygiene operations are more constrained in a microgravity environment because they require more space, privacy, and can generate more liquid FOD. On ISS, crew used around 250 mL of water per shower; any hygiene design should accommodate this much water at a minimum.

3.1.1 Dedicated Hygiene Location

One of the most important lessons learned over the life of the ISS program was the importance of a dedicated hygiene area. The two most fundamental aspects of a hygiene location design are 1) provide crew privacy, and 2) contain fluids (e.g., water, shampoo, etc.) to prevent water from reaching electronics and to mitigate microbial growth in a spacecraft.

Without a dedicated location on ISS, hygiene was assigned to several different areas of ISS over the years, each designed for a different operation than hygiene. They each had to be outfitted with hardware solutions to mitigate fluid release, and there was not a single option that did not impact some other nominal operation.

The enclosed toilet volume was the first location to accommodate hygiene operations on the US side of the ISS. It was quickly determined to be unacceptable because it did not provide ideal hygienic conditions, was uncomfortable for crew, and made the toilet unavailable anytime crew was performing their hygiene in the volume. The unacceptability of the toilet volume as a hygiene space led crew to use alternate areas such as the Crew Quarters, the area immediately outside of the toilet, and the stowage module.

The stowage module was retrofitted with retractable, hydrophobic curtains and was more comfortable than the toilet volume. While this deconflicted crew hygiene from toilet ops, hygiene now conflicted with stowage operations, which were near constant on board the ISS.

Ultimately, without a dedicated hygiene location, there was no option for ISS hygiene that did not impact some other operation for a fellow crewmember.

Figure 3-1. Hygiene Covers Deployed in the Stowage Module.

3.2 HARDWARE CONSIDERATIONS

Beyond having a dedicated space, any hygiene location should prioritize crew privacy and fluid containment in its design.

3.2.1 Privacy

Hygiene locations should be clear from main translation paths and must be out of the way of video feeds or camera views. A privacy curtain can be designed and flown to provide additional privacy between crewmembers. These curtains should be opaque and cover as much space as possible. Designing for the most privacy possible ensures that everyone on board will be comfortable.

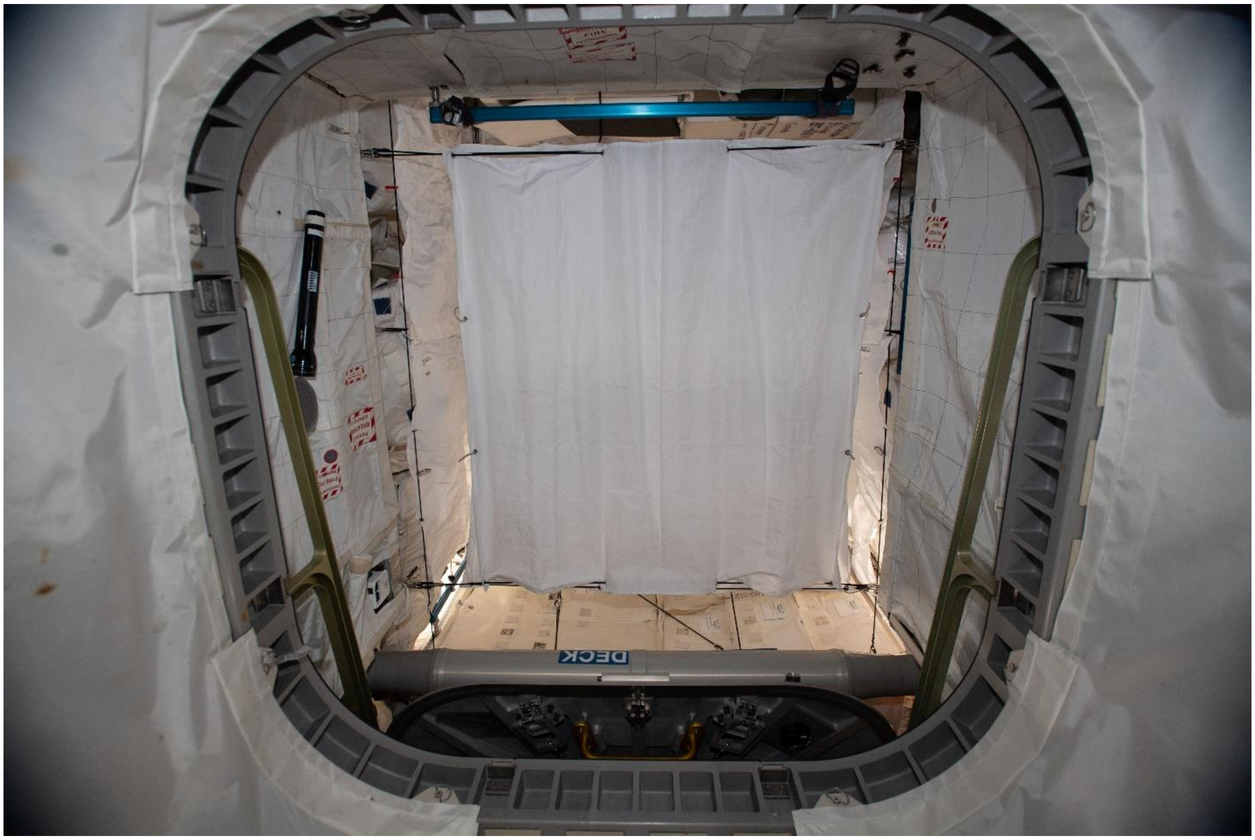

Figure 3-2. Stowage Module Hygiene Privacy Curtain.
Larger curtain launched at crew request to provide more privacy.

Moreover, it is highly desired to designate a dry hygiene location in addition to a wet location. Not only was this preferred by crew, but it deconflicted hygiene operations and provided more day-to-day operational flexibility.

A hygiene volume should also include a dedicated space to keep crew hygiene supplies (e.g., washcloths, towels, razors, soap, etc.). Even if a vehicle cannot accommodate a dedicated hygiene volume, having a designated space for hygiene items helped provide crew organization options that cut down on the amount of time required for hygiene ops.

3.2.2 Liquid Containment

One of the most challenging aspects of hygiene in microgravity is the liberation of water and hygiene products, which can contribute to microbial growth in a spacecraft.

3.2.2.1 Surfaces

It is recommended that a volume intended for hygiene contain antimicrobial surfaces and be designed for easy cleaning. Additionally, any hardware in the hygiene volume (e.g., closeout panels, air inlets, etc.) should be corrosion-resistant and easily cleaned.

Consider limiting Velcro in the hygiene space. Although crew should have restraints and mobility aids to assist in positioning themselves and needed items during hygiene, Velcro is difficult to keep clean. Consider alternate restraints like bungees, which can be returned to ground, refurbished, and re-flown. Additionally, various clips (e.g., binder clips, book clips, etc.) are excellent at keeping items out of the way and can help with drying clothes and towels.

On board the ISS, hygiene curtains were used to protect hardware and stowage in the stowage module. The curtains effectively protected the hardware; however, they became dirty over time. Any hygiene curtains, covers, or walls should be an easily cleanable material. Additionally, consider flying spares at regular intervals so crew can change them out as needed.

3.2.2.2 Environment

Regarding the environment of the hygiene space, airflow should be adequate to dry surfaces and clothing/towels, but not too much airflow as to make hygiene ops uncomfortable in the area. High flow can create a colder environment and, in fact, make it more challenging to prevent FOD liberation. Considering both air flow and air temperature during design is crucial to ensure a comfortable environment for crew during bathing ops. Air intake vents must be compatible with fluid and outfitted with fine-mesh screens to collect FOD (e.g., hair, fingernail clippings, etc.).

Additionally, the hygiene area should be designed with adequate lighting so crew can see what they are doing. Furthermore, some sort of mirror should be made available so crew can see themselves. Shatterable materials should be avoided on board a space vehicle, so glass mirrors should be avoided, but crew will need a reflective surface to perform tasks like shaving.

3.3 OPERATIONAL CONSIDERATIONS

Coordination with crew on their individual needs is important for habitability in general, but critical for hygiene. Individuals' needs will be different based on a multitude of factors such as gender, skin type, hair texture, hair length, etc. Coordinating with crew is critical for ensuring their needs will be met during their mission.

3.3.1 Scheduling

When scheduling a crewmember's day during a mission, it was critical to consider when they performed habitability operations; crew needed to do these tasks regardless of the mission, and planning with these tasks in mind ensured they could meet the day's mission objectives on time.

For hygiene, duration was slightly different for each crewmember. However, they each needed hygiene time after waking, after exercising, and before sleep. Some crew preferred to fit in their longer wet hygiene ops after waking, some before sleep, and some in the middle of the day depending on their schedule. If a crewmember's exercise activities were split, they needed to perform hygiene after both, which increased the time required for hygiene overall that day.

Different hair lengths and textures required different care routines. Longer hair took a lot longer to wash and required additional space. Some crewmembers needed a longer block of time once every few days or weeks for their hair care, while some needed a shorter block every day. Crewmembers should be individually coordinated with to understand their unique needs and preferences.

3.3.2 Stowage

Crewmembers preferred to have space at or near the hygiene volume to keep their hygiene products stowed for efficiency. Even if using the same products, crewmembers largely preferred to have personal bottles of hygiene products as opposed to sharing items. From a psychological standpoint, having their own dedicated products provided crewmembers a small measure of privacy and personal ownership, which supported mental health during a mission. From a practical standpoint, personal bottles allowed multiple crewmembers to perform hygiene simultaneously in a primary and secondary approved location. Individual hygiene supply kits increased efficiency and enabled crew flexibility, especially when crew were time constrained.

3.3.3 FOD Mitigation

Crew used several techniques to limit FOD liberation. When performing shaving/hair cutting/nail clipping tasks, crew found it best to perform near an air inlet to carry any particulate to a filter. The air flow near an inlet helped contain any cuttings or clippings. Crew then gathered the FOD with tape, and finally wiped the inlet clean.

Crew also found that starting with small amounts of product then dispensing more as needed prevented liberating liquids and wasting product. Additionally, performing hygiene tasks more slowly and carefully was very effective.

3.3.4 Cleaning

Even if a hygiene location is designed with antimicrobial surfaces, hygiene curtains, and adequate environmental conditions to limit microbial growth, the area will still need regular cleanings. Crewmembers tidied up after their hygiene ops in consideration for their crewmates and their shared space, but additional time was allocated each week to thoroughly clean, disinfect, and dry the area. Even small amounts of moisture were enough to sustain bacteria on board, so dedicating time to clean helped limit the amount of microbial growth in the hygiene area that could spread to the rest of the vehicle.

For cleaning functionally, an important consideration is a solution that allows for the cleaning of soft goods such as a hygiene curtain. Consider that in microgravity, attempting to clean a soft surface with no reaction force/friction will prove difficult. A solution to keep soft goods taut to clean them effectively is highly desired.

4.0 GALLEY

4.1 OVERVIEW

The Galley provided the volume and hardware to support crew meal preparation and dining. It accommodated two critical crew needs: the ability to prepare and consume meals, and the ability to meet as a crew in a relaxed, social space.

Good nutrition is key to keeping crewmembers healthy and productive while living and working in space for long durations. Getting sufficient nutrients and calories was complicated by the fact that sensations of hunger and thirst were often dulled in microgravity, as was taste. The ability to rehydrate, heat, and cool food and beverages was important to creating enjoyable meals that the crew wanted to consume.

Dining as a crew was vital to crew morale. Crew described the joint meal as “sacred” and “the highlight of the day.” When asked what habitability feature most maintained a good sense of emotional wellbeing for the team, one crewmember responded that a common food prep/dining area was number one in promoting team cohesion.

The ideal galley provides hot, ambient, and cold water; heats and chills food and beverages; accommodates stowage for food, utensils, condiments, and cleaning supplies; and allows all crewmembers to dine together in a shared volume.

4.2 HARDWARE CONSIDERATIONS

4.2.1 Cleanability

The Galley area was at higher risk for microbial growth due to the food preparation and consumption. Even with the most careful crewmembers, food and beverages splattered and spilled, and particles ended up everywhere. All surfaces in a galley, including the surrounding surfaces, must be easily cleanable. Any nooks and crannies will be difficult or impossible to clean. Use of fabric in the areas is discouraged as food stains may not be removable from fabric. On the ISS, stowage racks with fabric covers were replaced due to the staining from food splatters.

The ventilation system must be compatible with floating food debris. Consider installing fine mesh screens over intake vents in the galley area. Escaped crumbs naturally collected on those vent screens where they could be vacuumed and disinfected during nominal housekeeping.

Trash was created in the Galley, including both wet and dry trash. Consideration should be given as to how to manage both. Trash disposal will be discussed more in the *Trash Management S*ection of this paper.

Figure 4-1. Rack in the ISS Galley Area, Stained with Food and Beverage Spills.

4.2.2 Water Dispenser

Water dispensing was necessary to provide potable water for crew consumption, but also as a water source for payloads and crew personal hygiene. The water dispenser on ISS was an important part of food preparation, in addition to providing crew's drinking water.

4.2.2.1 Dispense Temperature

Water should minimally be supplied at hot and ambient temperatures; supplying cold water will enhance habitability. Hot water was most effective at rehydrating food and beverages but was not ideal for foods that crew preferred to eat at a cooler temperature. Therefore, ambient water was preferred to rehydrate some food items and was used for purposes other than food rehydration (like supplying water for experiments). Providing cold water could allow crew to dispense and immediately consume cold drinking water, which would be a benefit over and above what ISS offered. If, like on ISS, only hot and ambient water are provided, cold stowage (discussed below) can be utilized to chill food and beverages.

4.2.2.2 Dispense Volume

Especially if used to rehydrate food and drinks, the water dispenser should have a selectable volume. Selectable volume will allow crew to dispense the correct amount required to effectively rehydrate a given food item. The selectable increments should be small enough to specify a rather precise volume to adjust for various food volumes and personal preferences. On ISS, the dispense volumes were 25-250 mL, in increments of 25 mL. The second-generation water dispenser on ISS had an additional custom dispense setting that could be set by ground command. This custom setting could be set to any volume and reduced crew time when repeated dispenses over 250 mL were required.

An option to immediately stop a dispense was included on ISS water dispensers. This enabled crewmembers to stop water flow mid-dispense for any reason. It was a convenience to enhance crew control over the dispense amount, but it also provided a layer of safety in case the dispenser over-dispensed or a food package disengaged from the dispenser.

4.2.2.3 Hygiene Water

Crew dispensed water for personal hygiene use (e.g., bathing, toothbrushing, shaving, etc.) in addition to food and beverage preparation. The crew required hygiene water (most often hot water) several times a day: in the morning, after exercise, and before sleep.

4.2.3 Food Warmer

Although hot water could be provided by the water dispenser, a food warmer was still necessary to enhance crew habitability. The addition of a food warmer provided the following benefits:

a. Food and beverages could be kept warm while rehydrating.

b. Foods that did not require rehydration could be heated to a desirable temperature prior to consumption.

c. It gave the crew the ability to prepare meals ahead of time and keep food warm until they were ready to eat. This gave them adaptability to meet their needs and still maintain a busy timeline.

d. Hygiene water could be kept warm for bathing.

    1. Crew could prepare hygiene supplies ahead of time and keep them warm in the food warmer until they found an ideal time for hygiene operations.

    2. Crew could save unused hygiene water, then reheat it later in a food warmer rather than dispensing more water.

4.2.3.1 Interior Volume

The food warmer should be sized to accommodate enough food for the full crew all at once. This will allow the crew to eat together or overlap their meal prep even when dining separately. The number of packages that comprise a full crew meal will depend on the serving size of each package as well as crew preferences and caloric needs, which will vary. The most ideal food warmer size from a habitability perspective is one that provides enough volume to accommodate all crew eating a large meal, but also can heat just a few items at a time.

Consideration should also be given to the types of food that will be provided. Any slots or pockets within the food warmer need to accept packages of varying sizes and packaging types. For example, some food sent to ISS was in relatively flat, flexible packaging, but other food was in hard-sided containers (e.g., cans) of varying depths.

4.2.3.2 Temperature Selection

NASA food warmers have not historically had an adjustable temperature. They heated food to ~180° F (82° C). Crewmembers determined food temperature by timing its duration in the food warmer rather than by selecting a precise temperature. This seemed to work well for diversified crews and avoided complicated food warmer operation.

Figure 4-2. The ISS Food Warmer (AKA ISS Suitcase Food Warmer) was Portable. It could heat up to 12 ISS food/beverage packages at a time but was not deep enough to accommodate cans well. Due to the small capacity, the ISS Food Warmer was often unable to close completely when cans were being heated. Packages could be heated on both sides of the single heating plate.

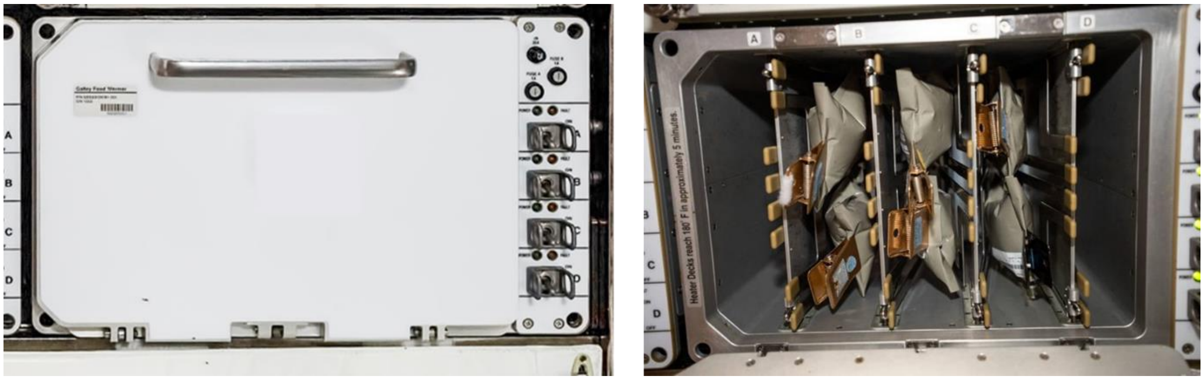

Figure 4-3. The Galley Food Warmer was Installed in the ISS Galley Rack. One Galley Food Warmer could heat up to 32 ISS food/beverage packages (including cans) at a time. Packages were heated by four vertical heater decks, which could be powered individually. Crew preferred this food warmer over the previous "suitcase" food warmer due to its capacity. The ability to power each heater deck individually may help in a situation where vehicle power has to be reduced or partially diverted.

4.2.4 Food Cold Stowage

Cold stowage will ideally provide for chilling food and drinks to refrigerator temperature (33-40° F or 0-4° C). For NASA Artemis missions, cold stowage is not a requirement due to power, mass, and volume concerns, but it is desired by crew, especially given that most water dispensers provide only hot and ambient water. Cold stowage will allow crew to keep food longer if they cannot consume it immediately after preparation. It may also allow for the provision of more perishable food items (including condiments), thus further enhancing the crew menu.

Freezing food or drinks was an infrequently used capability on ISS, but it boosted crew morale to have the option. If a freezer function is provided, it should be an addition to the refrigerator function rather than a replacement of it. Crew used refrigeration too frequently to lose that capability.

4.2.4.1 Nominal Use

Crew most frequently used the ISS refrigerator to chill beverages – often stockpiling drinks in the fridge so that they were ready on-demand – but they also stowed food and condiments when there was room. Crew used the ISS freezer for ice cream and to create popsicles from nominal beverages.

4.2.4.2 Interior Volume

Cold stowage should, at a minimum, accommodate a drink package for each crewmember – at least enough for each crewmember to have a minimum of one beverage chilling at all times – and provide some space for common items, like condiments.

4.2.5 Table/Dining Surface

Crew needs to have a surface for individual and group dining, and one that also serves as a stowage area for food packages, condiments, utensils, and clean-up supplies. A dining surface was important enough to ISS crew that, while one was not originally provided on the US side of the ISS, crew built one of their own from scavenged hardware. The dining surface serves not only as a table for meals, but also as a gathering place for crew to relax and reconnect after a long workday.

4.2.5.1 Table Size and Shape

The table should be large enough for all crew to dine at once on a common surface. It is also preferrable for the table to remain deployed at all times, to accommodate individual dining times and preferences. Consider what shape and orientation fits best in the volume. A configurable table – one that collapses, expands, or can be stowed when not in use – is acceptable as long as it is easily and quickly deployed and configured per crew preference.

4.2.5.2 Hardware Restraints

The dining surface needs to restrain food, beverages, utensils, etc. Velcro was most often used on ISS, but it collected oils and stains and was not easy to clean. Easily cleanable restraints, or restraints that could be easily replaced, should be considered.

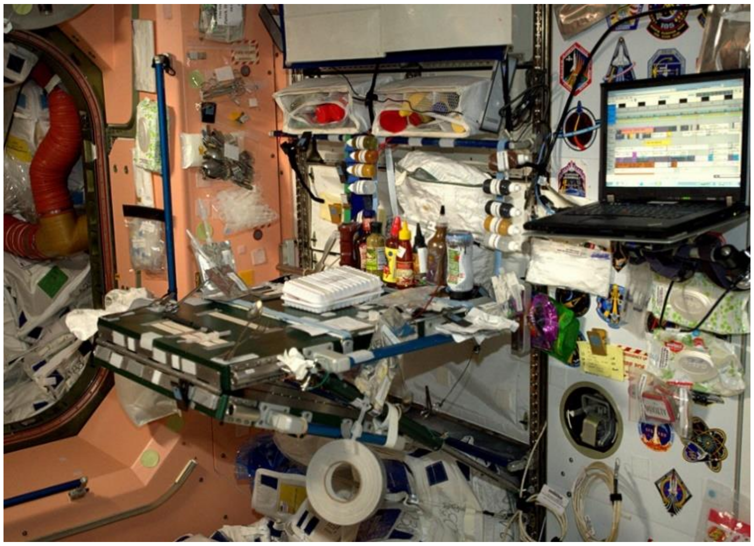

Figure 4-4. ISS Dining Table.

Half of the table was folded underneath to keep the table small most of the time, but the table was expanded for full-crew meals. Utensils and food items had small Velcro pieces that attached to the Velcro on the table.

4.2.6 Utensils

Each ISS crewmember was provided with a reusable set of utensils. There was no dishwasher on ISS, so utensils were cleaned with hot water from the water dispenser or with anti-microbial wipes. Individually packed, single-use utensils might seem cleaner, but would create a lot of trash that could not be readily disposed of. ISS utensil sets typically included a knife, fork, long spoon (to reach into deep food packages), and a pair of scissors (to cut open the food packages). Of those, long spoons were the most used items and scissors were generally shared. If canned food was provided, a can opener would also likely be needed.

4.2.7 Food Storage

Ideally, several days' worth of unprepared food is stowed near the galley. Having a large variety of food nearby makes it easy for crew to select what they want to eat in the moment.

In addition to food, any support hardware, like utensils, straws, extra drink bags, and cleaning items should also have a stowage location within arm's reach.

Some division of food is recommended to streamline food preparation. On ISS, food was divided by food type (e.g., beverages, main dishes, and desserts in separate bags). This worked well to help crew easily locate food, yet still allowed for crew to select individual items from each bag.

4.3 OPERATIONAL CONSIDERATIONS

4.3.1 Location

At least once daily, the full crew gathered to eat together in the Galley. Consider the space, airflow, and restraints required to accommodate the full crew all at once. As mentioned earlier, maintaining a space for the full crew to gather was vital for morale and crew cohesion.

The galley should be sufficiently separated from the toilet, exercise, and hygiene areas to maintain cleanliness, avoid contamination of food prep surfaces, and limit noise and odor issues. It should also be separated from any critical hardware where contamination to the hardware will be a concern. For example, it is undesirable for food and beverage splatters to land on hatch seals, electrical sources, or any Airlock hardware.

Collocating galley hardware is advisable because it will make it much easier for crew to prepare and eat food. But it also helps to have a cohesive galley that is more easily separated from other locations, as mentioned above.

4.3.2 Schedule of Use

The galley will best serve the crew if it is available at all times. At a minimum, it will need to accommodate flexible crew schedules. Crew will desire to have one joint meal, typically at the end of the day. Therefore, the galley must make provision for many items being prepared and eaten at the same time. But crew will also dine, snack, and refill beverages individually throughout the day, depending on crew preference and task timelines. Multiple crewmembers reported that it was difficult to get sufficient calories, so enabling them to snack throughout the day supplemented what they got during mealtime.

If galley use must be restricted, additional preparation time will need to be accounted for. Crew will need time to power on hardware, allow it to reach temperature, then prepare their food. It is a good idea to limit how much time hardware will require before it is ready to prepare food. However, any wait time is less than ideal because it will discourage crew from eating whenever they are hungry and impact how many calories they consume.

4.3.3 Food/Beverage Identification

With multiple crewmembers using a common galley, it is important that each person can identify their personal food packages, utensils, etc. Reusable items, like utensils, may be personalized with names, initials, color-coded labels, or some other identifier. Food and beverage packages can be simply labeled with a Sharpie. If the galley hardware can accommodate the space, each crewmember can put their items in a designated location. For example, the crewmembers on ISS found it useful for each crewmember to claim one heater deck within the food warmer. They heated their food on that specific heater deck so as not to confuse their food items with others being heated at the same time.

4.3.4 Crew Restraints

The galley is a location where crew will spend long durations, multiple times a day. Restraints here should be configurable but also comfortable for repeated and long-duration use. Refer to the *Restraints and Mobility Aids* Section of this paper for more information on the design and use of restraints.

4.3.5 Dual Use Galley Hardware

It is not uncommon for hardware to serve multiple purposes due to spatial, financial, or launch mass constraints. For example, the dining table may also serve as a workbench, or the refrigerator may cool experiments or medicines in addition to food. Before that is accepted as the default, it is important to determine how dual use will affect crew's ability to use the galley as desired and how it will affect the other user.

As mentioned above, it is desirable that the galley be available to crew at all times. Therefore, crewmembers should be enabled to monitor and control dual use as they see fit to preserve their access to the galley. Any dual user that has requirements for specific conditions (e.g., must be kept to a certain temperature without being disturbed) is not a good candidate for deployment within the galley – where crew will jostle the table and open the Food Warmer and refrigerator multiple times a day. Additionally, anything that might contaminate crew's food supply should not be stowed in the galley volume.

4.3.6 Maintenance

It cannot be overstated how important the galley is to meeting crew physical and psychological needs. Any failed galley component directly impacts crew morale. Before a failure, there should be plans in place to repair or replace any hardware as needed. Ensure that spare parts or replacement units are always available. Have procedures ready for execution. Anything that can be planned ahead of time will reduce crew anxiety when – not if – a failure occurs.

5.0 HOUSEKEEPING

5.1 OVERVIEW AND PHILOSOPHY

The importance of housekeeping during long-duration space missions cannot be overstated. At its core, a spacecraft is a dwelling for crew to live and work. As such, it must be cleaned regularly and maintained to ensure hardware functionality and to promote crew quality of life.

Housekeeping is defined as activities that support cleaning and elimination of contamination on surfaces and air inlets. Simply stated, it is standard upkeep of the living space, akin to housekeeping on Earth. Housekeeping activities include general surface cleaning, vacuum cleaning, and cleaning of personal work and living areas such as sleep compartments. Ground teams and on-orbit crew work together to establish cleaning priorities from week to week. However, crew should be able to complete housekeeping with little to no Ground Team involvement. And, although a dedicated time for weekly housekeeping was scheduled on ISS, small cleaning tasks were completed as needed throughout the week, without ground knowledge or assistance. Housekeeping hardware (e.g., wipes, vacuum cleaner, etc.) was always available for crew use at their discretion.

It is also important to define what housekeeping is not. Hardware that has a required cleaning frequency or that requires reconfiguration, power off prior to cleaning, special tools, or a procedure to clean is considered a preventive maintenance task, not housekeeping.

5.2 HARDWARE CONSIDERATIONS

5.2.1 Spacecraft Design

Spacecraft structures should be designed with cleaning accessibility in mind. In general, hard surfaces are easier to clean than soft surfaces. The use of felt, fabric, mesh, etc. should be minimized particularly in high traffic areas or historically “dirty” areas like the galley and toilet compartment. Easily cleanable covers should be designed for areas where soft surfaces are unavoidable, like sleep compartments. Due to the nature of dust migration, dust will inevitably accumulate across all surfaces and areas on board. Designs with “hidey holes” or narrow gaps between structures should be minimized because these can be difficult or near impossible for crew to clean effectively given the constraints of their tools and environment on board.

There are many sources of dust and FOD on a spacecraft. The human contribution of such debris consists of dead skin cells, hair, fingernail clippings, and food particles released while consuming food. Other contributors include clothing/towel lint, maintenance activities and operations that create or liberate debris, payload experiments, and certain spacecraft systems. Additionally, FOD can be introduced during visiting vehicle ingress when crew open hatches and vehicle atmospheres mix.

In a microgravity environment, dust does not fall to the ground; rather, it becomes entrained in the air stream and caught by the first filter it contacts at an air intake. Environmental Control and Life Support System (ECLSS) design must include a robust filtration system to effectively remove particulate from the cabin environment. Moreover, ECLSS subsystem components such as diffusers, Inter-Module Ventilation (IMV) grilles, and filter grates should be designed with cleaning in mind. For example, IMV inlet screens should have gaps wide enough to insert a vacuum cleaner attachment or be designed such that accessing the filter is intuitive and does not require additional tools.

Figure 5-1. Cabin Air Bacteria Filter Assembly Before (right) and After (left) Cleaning.

Failure to or an inability to effectively clean filters and grilles has significant consequences for both crew health and hardware performance. From a system perspective, a degraded IMV restricts intra-module airflow, which reduces cabin mixing and creates stagnant air pockets, resulting in an uninhabitable atmosphere. Additionally, degraded IMV airflow causes IMV fans to operate in a stall configuration which can both damage the fan and increase the operational noise, which can have further negative impacts on crew health. Moreover, significant dust accumulation occludes inlet vents, reducing hardware cooling efficacy. Without proper cleaning, this can damage hardware to the point of failure. The presence of uncaptured particles poses a risk to crew health as potential eye irritants or aspiration into the upper airway which can result in allergic responses (e.g., sneezing, stuffiness).

5.2.2 Housekeeping Hardware

Both NASA-designed and Commercial Off the Shelf (COTS) housekeeping hardware have been used effectively in spaceflight.

5.2.2.1 Vacuum Cleaners and Accessories

Vacuum cleaners and accessories are an integral piece of the housekeeping hardware ensemble. The housekeeping vacuum cleaner is used to clean dry and non-hazardous debris (for wet or hazardous debris cleaning, please refer to the next section). Vacuum cleaners should have robust suction capabilities and ideally feature multiple power level settings. Lower settings can be used to clean more sensitive surfaces, such as HEPA filters, while higher settings are more effective at cleaning a wider variety of surfaces. Using a vacuum at higher power settings results in more power draw, so a vehicle must be capable of powering the selected vacuum cleaner to prevent circuit tripping or loss of power. The vacuum cleaner will need to be used everywhere throughout the vehicle; ensure there are a variety of available and adequate plug-in locations to power the vacuum that take into consideration potential vacuum cord length constraints. On ISS, the vacuum cleaner was capable of reaching end-to-end of every module.

A battery powered vacuum cleaner (cordless) may be preferred over providing dedicated plug-in locations for a corded vacuum. Cordless vacuums have the added benefit of allowing crew to access hard-to-reach locations that may other be inaccessible due to vacuum hose or power cable length. Consider the tradeoffs if selecting a cordless vacuum such as battery life, charging time, battery degradation and suction power.

In general, vacuums and batteries pose flammability concerns. If the vacuum cleaner casing is made of flammable material (most plastics are flammable in a high oxygen environment), be certain that it is stowed inside a non-flammable container. Likewise, batteries should always be isolated from other vacuum hardware and stowed inside a stowage bag that will prevent fire propagation.

Vacuum cleaner accessories can include, but are not limited to, any combination of a suction hose, hose extension, crevice tool, surface tool, and brush tool. Crew can use these at their discretion during housekeeping. When selecting the suite of vacuum accessories, it is important to consider the types of areas that crew may need to access, particularly small and hard to reach areas. Lessons learned should be considered for which tools have worked most effectively for different uses.

Figure 5-2. ISS Vacuum Cleaner.
(Left to right): surface tool, brush tool, flexible modular cleaning tool, crevice tool.

5.2.2.2 Other Vacuum Considerations

Vacuum cleaners might be used to clean up hazardous debris. Once used on hazardous debris, the vacuum may be limited in its future use or require disposal, depending on the use. It is advisable to have multiple vacuum cleaners available to account for such occurrences.

On ISS, there was a vacuum cleaner dedicated to wet debris, one dedicated to dry/hazardous debris, and multiple dedicated to dry/non-hazardous debris. Recall that for housekeeping, the stipulation was dry and non-hazardous debris. The additional vacuums for wet and hazardous debris were provided for cleaning outside of nominal housekeeping for use with payloads or contingency spills. When providing multiple vacuum cleaners, clearly label each vacuum for its designated purpose and provide nominal maintenance instructions for each.

5.2.2.3 Vacuum Consumables

Depending on vacuum design, consumables such as vacuum bags and HEPA filters may be required and should be kept in sufficient supply. Generically, it is helpful to replace vacuum bags near air intake vents so that liberated dust from the bag (inevitable in microgravity) will be pulled into the vent screen rather than released into the cabin air. Personal Protective Equipment (PPE), like dust masks and goggles, should be worn to mitigate inadvertent crew exposure to a bag's contents. The level of PPE required should be dictated by the nature and toxicity of the debris. For example, to change a vacuum bag containing only dry, non-hazardous debris on ISS, crewmembers were not required to wear PPE and only one crew member was required to perform the operation. Conversely, to change a vacuum bag containing wet or hazardous debris, two crewmembers donning safety goggles, dust mask, and nitrile gloves were required. The second crewmember was required to watch for escaped hazardous debris and to assist with vacuum bag containment.

5.2.2.4 Wipes

Wipes should be kept in great supply due to the frequency of their use. Generically, wipes can be broken down into three categories: disinfectant wipes, wet wipes, and dry wipes.

Disinfectant wipes are used frequently in housekeeping procedures for cleaning commonly touched surfaces, IMV grilles, and diffusers, including areas that crew may hang their worn clothing or personal hygiene items for drying. Disinfectant wipes must have an active ingredient such as hydrogen peroxide to inhibit microbial growth.

Wet wipes (e.g., baby wipes) are used for personal cleaning like handwashing and should not be used for housekeeping. COTS wet wipes can leave residue that feeds microbes, making them unsuitable for nominal surface cleaning. Crew may find wet wipes more effective than disinfectant wipes at cleaning food and particle debris from surfaces. In these cases, whenever wet wipes are used on hardware or common surfaces, they must be succeeded with a disinfectant wipe.

Dry wipes are all-purpose and can be used for personal use or cleaning up non-hazardous spills. They can also be wetted when water is the preferred cleaning medium.

Figure 5-3. Wipes.
(Top to bottom): disinfectant wipes, wet wipes, dry wipes.

5.3 OPERATIONAL CONSIDERATIONS

Housekeeping can have a significant effect on crew health. ISS crewmembers experienced allergy-like symptoms (e.g., stuffiness, sneezing) when housekeeping was chronically delayed. Time to execute housekeeping should be protected and scheduled every week, without fail. Deferring housekeeping should not be taken lightly; the compound effects of deferring housekeeping will result in additional time and effort to clean and mitigate issues. On ISS, housekeeping was typically scheduled for the weekend.

From a program perspective, calculating weekly housekeeping hours should involve identifying what needs to be cleaned, estimating the length of time to clean each item, and dividing that total amount of time by the number of available crewmembers. In addition to the scheduled housekeeping, consider that crew will likely perform impromptu and unscheduled cleaning as needed throughout daily operations.

ISS has a long history with housekeeping. When the station was new, less time was required to clean, but as the station aged and more crew began to live and work on board, the time allocated to cleaning increased. The evolution of ISS housekeeping was also influenced by crew feedback. In general, whatever number is derived for total weekly housekeeping hours should be assessed periodically to ensure that it is reflective of the current state of the vehicle.

It is likely that there will not be time enough to clean every surface or vacuum every corner of a spacecraft, especially on a regular schedule. Instead, crew should be provided with a general task reference that recommends areas expected to need cleaning on a regular basis. Crew can use that reference to help prioritize cleaning locations and frequency whether that be scheduled weekend housekeeping or daily cleaning. The reference should also provide general cleaning guidelines. ISS experience emphasized that crew should prioritize cleaning the modules that were expected to be the dirtiest; these were modules where crew meals, exercise, and waste management occurred. However, the crew will have more insight than ground teams as to the cleanliness of a spacecraft so they should also be allowed to focus on areas they deem more critical.

A housekeeping reference should also include a prompt for crew to notify ground teams about unexpected hardware configurations or upon discovery of condensation or microbial growth. Increased cleaning or operational changes may be implemented in areas of concern.

6.0 STOWAGE

6.1 DESCRIPTION AND OVERVIEW

This section will focus primarily on lessons learned from ISS stowage operations. This includes proper containers, methods for managing stowage, and the criticality of limiting stowage and managing configuration to preserve crew time and habitability. This section also addresses stowage tracking, which is a vital part of mission planning and execution.

Inefficient stowage configuration and/or management had detrimental impacts on crew habitability and timelines. Lost or misplaced items often resulted in the crew expending additional time searching for that item. As stowage accumulated, often items were stowed in non-stowage locations. When activities called for space to be utilized, the time needed to move and replace items after the activity delayed the crew from performing the intended activity. Stowage accumulation also resulted in desired items being buried or inaccessible unless the top layer was removed, placed elsewhere, and then placed back in the original location. All of this took valuable time.

In addition to time impacts, there was a mental aspect of disorganized stowage. Living and working in a cluttered environment can cause stress and anxiety. This can result in lower productivity or trigger coping and avoidance strategies. It can create a “brain dance,” i.e., agitation and inability to think clearly amongst the stuff.

Stowage required an efficient layout. Strategies that were considered included reach zones, habitable volume, and order of operations with respect to the flight phase in which the stowed items were used.

Presleep and post sleep activities also created a high stowage use period that produced clutter. Clothing, food, hygiene supplies, and various personal items were deployed during this time. Clutter was a big factor on ISS that vehicle designers should always be aware of because it affected Net Habitable Volume (NHV). Peak use and NHV were directly affected by container size and layout as well.

6.2 HARDWARE CONSIDERATIONS

6.2.1 Racks

Stowage racks were used to deliver and stow logistics. Stowage racks were not powered and had no utility connections. The types of stowage racks used on ISS included Zero-G Stowage Racks (ZSR) and Resupply Stowage Racks (RSR). ZSRs were soft-sided and were typically used only to stow logistics on board the ISS, and not launched with cargo in them. RSRs were rigid and typically used to secure logistics during launch. It was most ideal when stowage lockers or drawers within the racks were sized to fit common stowage bags. Logistics delivered within stowage racks were transferred to stowage locations. The crew’s preferred type of stowage rack was the ZSRs. These racks were configurable such that shelves or dividers could be added or removed easily. Additionally, the soft sides could conform to accommodate the stowage placed inside it.

Stowage racks of any type should not become overfilled. Overfilled racks decreased crew efficiency as they took significant additional time to remove items and then jam them back into that location later.

Rack drawers were generally a useful feature. The interface should be straightforward, easy to open, and easy to close. However, it was a significant problem when rack drawers became overpacked on ISS.

6.2.2 Bags

6.2.2.1 Primary Stowage Bags

Bags with specific uses should be color coded. For example, emergency bags should be red or orange for quick identification; trash bags should also be uniquely colored to aid in trash transfer operations. Other colors (e.g., for food bags, water bags) could also be beneficial. However, color coding and labeling on general use bags should allow flexibility, so if a bag is emptied it may be reused with different hardware as needed. It is suggested to use a neutral color or colored labels (which can be changed) rather than colored fabric or stitching for these general use bags. Color can also be used to indicate usage or final destination, e.g., green labels indicate “Return to Earth,” white labels indicate “nominal onboard operations,” etc.

Stowage bags should be identifiable (e.g., by serial number) from any side. All items should have labels that contain easily readable information including item name and serial number or reference identification.

Straps are preferred so that crew can grip a bag, strap bags together, or strap a bag to a bungee. Bags that are thin enough to fold and stow when they are empty were preferred over thicker bags due to their flexibility, ease of folding, and smaller footprint when empty.

Velcro on the inside of a stowage bag was a useful feature. The crew often used an empty bag as a temporary stowage container for hardware required for a task or activity. The Velcro inside the bags was very useful to contain items. Zippered lids allowed a crewmember to open the lid only the amount needed to access small items in the bag without having to open all the way, thus possibly releasing everything inside.

Handles on the bags facilitated ease in transferring and stowing them. Several handles placed around the bag allowed for versatility regarding orientation when stowing a bag in various locations.

Pockets in bags were useful, especially for stowing very small items like caps or jump drives. Transparent or mesh-type lids that allowed the contents to be seen were considered a useful feature. Being able to see what was in the bag before opening it was helpful to crew.

6.2.2.2 Ziplock Bags, Small Containers

Ziplock Bags and Kynar Bags were used to contain smaller items. Generally, Ziplock Bags were the preferred container because they were commercially available. The advantages of the Kynar Bags were that they were a little stiffer and therefore better contained some items in microgravity, and they closed a little easier and more securely than Ziplock Bags. Finally, but very important in a high-oxygen environment, Kynar Bags were less flammable than Ziplock Bags. On ISS, Kynar Bags could be left in the open cabin, but Ziplock Bags could not be due to the flammability concern.

Kits of items stowed within small containers should take full advantage of using friction fit for stowing items. Organize items in line with the setup/disassembly procedures. A good organization method would be to have a rigid or semi-rigid container with labeled, cushioned slots in which to stow items. This type of container will save crew time over having to search and sort through multiple bags within the kit.

Small mesh containers were good, especially for temporarily stowed items for a task or items that would frequently be accessed.

6.2.2.3 Trash Bags

Trash bags should be medium sized. Small bags filled quickly, became plentiful, and thus hard to contain as group. They also did not accommodate larger trash items. Very large bags were difficult to continually add smaller items into as the trash already contained tended to escape. Trash bags should have odor control, especially for the toilet and wet trash. More information is given in the *Trash Management* Section of this paper.

6.2.3 Stowage Restraints

Additional information about stowage restraints is in the *Restraints and Mobility Aids* Section of this paper.

6.2.3.1 Bungees

Bungees were useful for restraining various stowage amounts from individual stowage bags to large groups in a mound or pile. Bungees should be deployed in stowage locations and near worksites to allow for quick temp stowage and restraining of items. Bungees were advantageous because they were extremely versatile and could be deployed or relocated quickly.

6.2.3.2 Straps

Straps were a more permanent stowage restraint than bungees. Straps should be easy to adjust and should secure items without the possibility of coming loose. Buckles should be easy to operate and fully disengage.

6.2.3.3 Velcro

Velcro had many advantages and therefore was usually in high demand by the crew; however, Velcro required safety controls for flammability, so its use in the open cabin was limited. Velcro strategically placed in the habitable volume allowed for efficient temporary placement of items and containers used for various tasks and activities.

6.3 OPERATIONAL CONSIDERATIONS

6.3.1 Limiting Stowage

A surplus of stowage resulted in loss of valuable space and crew time, along with the impacts related to physical and visual clutter in the crew's living and working environment. Consumables, supplies, equipment, spares, etc., should be limited to what is needed to complete the mission. Spares should be limited to critical failure items that need to be replaced during the mission. Packing materials should be limited as much as possible to reduce volume and trash. Accumulation of used hardware, degraded spares, or other items for future or unplanned uses should be minimized to avoid overloading the stowage volumes.

6.3.2 Layout Efficiency

Layout efficiency directly affected the choreography of on-orbit operations. Future programs should consider arranging items in order of need to reduce gather times. Collocating items and stowing them near their point-of-use, also commonly referred to as temp stowing, will do the same. On ISS, the crew was frequently in close contact with each other while trying to access stowage areas at the same time. Future programs should consider utilization frequency and human factors in designing stowage locations. For example, a stowage location adjacent to the toilet can cause impacts to privacy and crew access.

Stowage volumes should accommodate nominal day-to-day operations, but also be sized to accommodate surges in stowage on board. For example, if many cargo bags must be quickly transferred out of a newly arrived resupply vehicle to access time-critical experiments, there should be adequate volume to accommodate those cargo bags without interfering with other operations. On ISS, overlapping stowage surges (e.g., unstowing the airlock to make room for Extravehicular Activity (EVA) preparation or early destow cargo bags from a resupply vehicle) often created timeline impacts and decreased crew efficiency. Rack front stowage should be avoided, because it blocks access to the rack itself and can impede the traffic flow of the module.

Items should be stowed in a container or location based on their size and usage. Obviously, large items should not be jammed into smaller locations, but the opposite is also true. Small items should not be stowed in large bags or locations because they can be very difficult to find among the jumble of other items.

6.3.2.1 Order of Operations

When volume was limited, stowage was a larger factor in the order of operations. Any given volume must accommodate sequential tasks, i.e., each succeeding operation may need to utilize the stowage space evacuated by the previous activity. For example, the crew may not be able to doff suits until launch restraints or seats are stowed. Therefore, seat stowage must be accomplished prior to suit doffing activities.

When designing a new vehicle, it is advised to not limit operations to only a predefined activity. Years of operations expertise has shown that multipurpose work volumes allow for changing tasks and order of operations. Vehicle design as well as stowage layouts should be generic enough to accommodate the stowage mass and volume.

6.3.2.2 Collocation

Stowage locations for on orbit supplies for any operation should be collocated. Assembling equipment was difficult in weightlessness and was exacerbated by having to open multiple stowage locations or hunt for parts throughout the cabin. In some cases where supplies were generic, such as wipes or batteries, a central stowage location for those was sufficient. However, a specific wipe or piece of hardware for a payload should be packed with the payload.

6.3.2.3 Point-of-Use Stowage

Items should be collocated near their point of usage when possible, e.g., food should be stowed near the galley, hygiene items should be stowed near the hygiene area and toilet systems, etc. This may mean stowing a small amount at the point of use, with refills stowed elsewhere.

6.3.3 Clothing

Individual clothing lockers with space between them was a desired stowage configuration. If one clothing locker was directly above or below another, the crewmember with the lower locker had to wait for their crewmate to close their locker. Distributing personal lockers such as clothing around the cabin also established personal space for each crewmember.

Clothing may also be stowed in a crewmember’s individual private sleep compartments or in portable containers that crew can place per their preference.

6.3.4 Food

Food stowage is discussed in the *Galley S*ection of this paper.

6.3.5 Supplies – Warehouses and Pantries

A stowage paradigm that worked well on ISS for generic, high frequency use supplies was the concept of warehouses and pantries. Warehouses were stowage containers of these supplies and they were kept in a stowage location outside of the main working/habitation volume. Pantries were stowage containers kept in a readily accessible location in the working volume. Each housed supplies by category. For example, there was a warehouse and pantry for office supplies, one for wipes, another for batteries, etc.

Crew gathered these supplies from the applicable pantry as needed. When the pantry was empty, the corresponding warehouse was retrieved and became the new pantry. The ground resupplied warehouses as needed to ensure that there were sufficient supplies on-orbit at all times. This worked well on ISS to alleviate stowage congestion in the working/habitation volume.

6.3.6 Safety Considerations

6.3.6.1 Medical Accommodations

Injured or ill crewmembers could cause mission plans to change. The working volume needed to treat medical conditions should be protected at all times, thus should be kept clear of stowage. There must always be enough working volume to treat the injured or ill crewmember without impeding the rest of the crew from safing the cockpit for return.

6.3.6.2 Protect Airflow

Crew must be careful to keep stowage out of airflow paths. When stowage is in front of an air vent, it created pockets of “stale” air where CO2 built up and oxygen was depleted. Stowage plans should never direct crew to place stowage in critical airflow paths, and crew should be trained to watch for and relocate any stowage temporarily or accidentally placed within an airflow path.

6.3.6.3 Electrical Consideration

Stowage bags were typically plastic or cloth and made of non-flammable material. Although fire-retardant, it was wise to keep such materials away from power sources to protect against flammability concerns.

6.4 TRACKING STOWAGE AND INVENTORY

Tracking of stowage and inventory was critical to successful mission execution. Crewmembers cannot possibly remember the location of every piece of hardware, tool, or consumable on board the vehicle. Tracking also insures that items can still be located as crews are cyclically arriving and departing. Lost items delayed or even prevented activity completion.

6.4.1 Inventory Management System

The Inventory Management System (IMS) was the ISS application developed to track the inventory and stowage of items on board and was accessible and updateable by both the crew and ground specialists.

The crew had primary responsibility for managing the onboard inventory and for providing this information to the ground specialists. All permanent moves from one onboard location to another were recorded in IMS as they were completed by the crew. Crew would inform the ground when they were complete with activities and would relay any changes to the stowage plan, such as items that were trashed or items that were restowed in a new location. Crew could inform the ground of stowage changes via a crew note or calldown; the ground would then update IMS based on the crew's report. Crew could also update IMS themselves.

The ground team was responsible for updating IMS for stowage changes prompted by their direction in crew activities. The ground teams were also responsible for adding and archiving items in the IMS database as they launched and returned.

6.4.2 Barcode Readers

6.4.2.1 Maximum Size

Crew recommended the barcode readers (BCR) be pocket sized to easily carry it with them. A suggested size of 8.0" x 2.0" x 2.0" would be acceptable.

6.4.2.2 Key Operational Features

1. One handed operation of the unit is recommended.

2. The scanner should be an integral part of the BCR, i.e., not a light pen.

3. BCRs should be able to transfer data electronically to the computer system hosting the IMS software.

4. The scanner should consistently be able to read bar codes from a distance of 0-6".

5. The scanner should reliably read all expected bar code label configurations, such as wrinkled packages, worn labels, etc.

6. The BCR/RFID software should easily access the IMS database.

7. The RFID "find feature of the application should allow the crew to quickly find and access misplaced items.

6.4.2.3 Memory

The BCR should have sufficient memory to store scanned data to minimize the number of downloads to the IMS software. The BCR on ISS retained a minimum of 500 bar code label scans. This number was to account for a worst-case scenario of performing an inventory status of a complete rack.

6.4.2.4 Success/Error Indicators

The BCR should emit an audible tone indicating a successful scan and a distinguishably different tone indicating an error. The screen should also have a visual indication of a successful scan or error.

6.4.2.5 Batteries

Batteries used in the BCR should be compatible with the selected battery charger. It is recommended that the battery charger be common to as much hardware as possible to limit how many chargers you need and to reduce crew time and frustration in managing multiple types of batteries. Battery life should be such that a crewmember can use the BCR without replacing batteries for a period of at least seven days of nominal IMS operations.

6.4.2.6 Display Screen

The BCR should have a readable display. The screen should provide indication of the BCR’s status and display key entries made by the crewmember.

6.4.2.7 Keyboard

The BCR should provide an alphanumeric keyboard usable without the aid of a stylus.

6.4.3 Radio Frequency Identification System

It is recommended that all areas containing stowage, or where stowage is translated through, be instrumented with radio frequency identification (RFID) antennas to maximize tracking coverage.

The ISS system used RFID readers and a network of antennas to track items with RFID tags on board. RFID readers on ISS were placed in each instrumented module. These radio/antenna systems emitted and received RF from items with RFID tags. The data collected were sent to an onboard controller. From there, data were sent to the ground where machine learning algorithms synthesized the data to infer item locations on board, which were input into the IMS database. This information was used to help crew find lost items and provide the ground with an overall awareness of the stowage configuration on board.

7.0 TRASH MANAGEMENT

7.1 DESCRIPTION AND OVERVIEW

This section focuses primarily on lessons learned from ISS trash management operations, including the vital need to limit trash and manage its configuration to preserve crew time and habitability. This section also addresses trash tracking, which was a critical part of mission planning and execution.

Trash issues had detrimental impacts on crew habitability and mission timelines. As trash accumulated on ISS, items were often stowed in non-trash locations, which impacted daily operations. Designing missions and vehicles for minimal trash generation manipulation saves valuable time and volume.

Objectives of effective trash management should include:

a. Contain hazardous material.

b. Contain odors.

c. Minimize crew time required to operate.

d. Minimize volume of trash.

e. Simple to operate and maintain.

7.2 HARDWARE CONSIDERATIONS

7.2.1 Trash Location

Trash bags should be staged in multiple locations across the vehicle so that the crew can immediately dispose of trash as soon as it is generated. Once these “point-of-use” bags are filled, crew should move them to a dedicated area for trash stowage. This dedicated space should not impact daily operations and should minimize crew’s exposure to odors.

Trash accumulation was an issue on ISS, regardless of disposal methods. Therefore, future missions should determine a designated stowage location within the habitable volume for long-term trash. The designated trash location should be outside of areas where crew would perform hygiene care, eating, sleep, exercise, and away from high traffic areas to avoid causing spatial, comfort, health, and contamination issues.

7.2.2 Trash Categories

On the ISS, trash was divided and tracked via multiple categories to allow for efficient disposal prioritization. For example, failed or unrecoverable critical hardware became trash, but had to be tracked so that ground teams were aware that the particular item was no longer functional or available.

The ISS used the following Trash Categories:

a. **Common trash** consisted of items that crew disposed of without notifying the ground. It included non-hazardous and typically frequent use items, e.g., paper, wipes, used tape, towels, etc. Common trash items were tracked at the consumable rate level. The ground team knew how many of each item crewmembers tended to use and planned ahead for disposal of those items. Common trash was subdivided into dry and wet trash.

    1. **Dry trash** was any trash that completely lacked moisture and would not spoil. It included not only used tissues and paper, but also reusable items such as used clothing and towels that were once wet but had been allowed to dry.

    2. **Wet trash** included all items that came into contact with moisture and could produce odors or off-gas, as well as materials that had been contaminated with biomatter. Examples included food packages, cleaning wipes, and toiletries. Wet trash was prioritized to be removed from the vehicle to minimize bacterial growth.

b. **Hardware trash** was hardware that was tracked as individual components. It was not considered common trash because ground teams needed to account for hardware trash. The hardware owners had input into the disposal plan for any hardware that they owned and the mass of hardware trash had to be included in disposal vehicle return trajectory calculations. Hardware trash was dry, but none of it was hazardous.

c. **Foam trash** was packing material used to protect hardware during launch. It was dry trash that was kept separate from all other dry trash because it was typically rectangular and bulky. Foam was often reused for packing of items to be returned to Earth, so it was separated from other trash to allow for easy retrieval.

d. **Hazardous trash** was potentially harmful to the crew. It included any trash that contained a toxic or flammable chemical as well as sharp objects, like broken glass. Sharp objects were classified as hazardous because, if they escaped, they presented an inhalation or eye hazard to crew. Hazardous trash was entirely and safely contained.

7.2.3 Trash Bags

Trash bags on ISS needed to be capable of effectively containing the three primary types of trash: dry, wet, and hazardous.

The primary consideration for dry waste was the size of the item to be contained. However, wet and hazardous trash presented additional considerations that required multiple levels of containment and containers that could be sealed to prevent liquid, gas, and odor escape. Wet items could leak, spoil, and generate odors that impacted habitability. Hazardous trash could leak or off-gas, presenting a crew safety concern.

Trash container selection should be directly related to the type of waste, how the waste ages, and trash stowage options. Future missions should manifest multiple types and sizes of trash bags depending on predetermined need.

Trash bags must also be capable of containing trash of various sizes. On ISS, small bags were useful for things that needed to be sealed up and disposed of quickly – typically wet or hazardous trash. However, small bags also fill quickly and could become plentiful, and thus hard to contain in a single trash stowage location. Small trash bags on ISS also could not accommodate larger trash items. Very large bags were necessary to contain larger trash that could not be broken down. But it was difficult to continually add smaller items to large bags because the trash already contained in the large bags tended to escape every time the bag was opened. Future missions should verify that the chosen trash bags provide sufficient odor control, especially for the waste management system (toilet) and wet trash.

7.2.4 Trash Compactor

Future missions should consider providing a trash compactor to improve trash management. An automatic trash compactor would reduce the time required to perform the trash compacting task and would also be beneficial to reduce the volume of trash overall.

7.3 OPERATIONAL CONSIDERATIONS

Trash management on ISS included daily collection and routine stowage of wet and dry trash as well as items that failed or had outlived their usefulness. Due to the limited volume that was available to stow trash, it was very important that all items were packed efficiently.

7.3.1 Trash Management

Trash management on board ISS included separating wet and dry trash to reduce the potential for mold and mildew growth. Separation of wet and dry trash on future missions may not be required if all bags (those used for both wet and dry) assume wet trash as a baseline and therefore would prevent release of fluids, odors, and microbial growth. Future missions should also consider any trash that may require special handling. For example, on ISS, the terminals on used batteries were taped over to prevent ignition in case of contact within the trash container. Also, hazardous materials usually had special handling and disposal instructions.

Launch packaging foam was a primary source of trash from a volumetric standpoint and ISS crews regularly reported foam as a stowage and trash management challenge. It was used to protect hardware during launch but, once on orbit, hardware rarely required foam containment and the foam simply filled space. While lightweight, foam still needed to be restrained to prevent floating into undesired areas. In the future, foam that will not be required for protection of returning hardware should be compacted as much as possible for disposal.

Optimal trash management may be achieved by limiting trash production. On ISS, packaging was a major source of trash. Limiting packaging, launch foam, and other forms of containment on future missions will likely reduce waste and increase crew efficiency. Future missions should consider using packing materials that can be reduced once on-orbit, such as bubble wrap, which can be deflated and trashed when it is no longer needed.

Lifecycle management should be considered crucial for everything launched into space. If an item has reached the end of its usefulness, it should be considered trash. Before launching any item, the criteria for its use and usefulness should be defined to allow the crew and/or ground to assess when to dispose or return it. The process to approve items for disposal should be streamlined and efficient. Ideally, everything that is launched should have a lifecycle plan including the plan for its disposal. While this would primarily be a ground process, on ISS, delays in approving disposal affected the crew’s habitability as trash built up. The crew should not have to wait days to get approval to discard broken or unused hardware.

7.3.2 Trash Disposal

Early in the ISS program, the crew spent hours collecting all the trash on board and relocating it to the disposal vehicle just before departure. Later in the program, in order to save crew time and preserve cabin habitability, a common trash container and stowage location were identified, and the crew started staging trash in that single location prior to it going on a disposal vehicle. This way when the disposal vehicle arrived, all that was required was to load the pre-staged bags on the vehicle.

Disposing of trash on an as-needed basis may be an optimal solution. Using a system to eject trash into the vacuum of space has proven beneficial on previous space vehicles. This allows for more rapid processing of trash rather than relying solely on disposal via visiting vehicle, as vehicle disposal is constrained by mass and launch/return scheduling. Trash compactors designed to reduce the volume of trash have also been considered but have never come to fruition on ISS.

7.4 TRACKING TRASH

Trash management on ISS included tracking trash to keep both the ground and crew apprised of what was available for use and what had been discarded.

Prior to launch, hardware owners should approve non-common trash items for disposal. The ground would then instruct crew when to dispose of items after their final use.

On ISS, ground teams utilized a disposal manifest list to generate trash gather and loading procedures that were executed by the crew to load full trash containers into their assigned vehicle location for disposal. After the crew executed disposals, a stowage tracking database was updated to indicate each item’s disposal action and locations.

8.0 RESTRAINTS AND MOBILITY AIDS

8.1 OVERVIEW AND PHILOSOPHY

Crewmembers restrain or translate themselves and hardware during virtually every moment living and working in space. To facilitate their success, it is incumbent on habitat designers to make restraint and mobility as natural and subconscious for crew in microgravity as it is for us on Earth. To understand how to accomplish this, it is useful to begin by discussing what feels natural to humans in the microgravity environment, based on an understanding of what restraint and mobility aid designs and methodology have proven successful for previously flown crewmembers.

Humans have evolved both to move and to plant themselves firmly to the ground by using their feet to balance body weight. Hands occasionally augment these functions, but they are typically left free. Crew carry these basic tendencies with them into space, but weightlessness has significant impacts on how they execute restraint and mobility.

When considering the philosophy of Restraints and Mobility Aids (R&MA), there are two critical characteristics that will help crew adapt to the spaceflight environment. These will be discussed in more detail later in this section.

1. Configurability and Variety: Providing a variety of R&MA hardware that can be easily reconfigured, augmented, and adapted enables crew to allow the hardware to fit their needs – needs that are often impossible to fully anticipate until the crew is in zero gravity and has adopted their own strategies for living and working in space.
2. Crew Management: Providing numerous attachment points and allowing crew to easily control where they will deploy R&MA enables crew to determine the best configuration for their living and working environment. It ensures adaptability as crewmembers, vehicle configuration, and hardware designs change throughout the life of a program.

8.1.1 Crew Restraint

Crew restraint in zero gravity is the ability to keep oneself stationary while performing tasks, especially tasks requiring the application of external forces and torques. For most tasks performed by humans on Earth, very little thought is given to counteracting these forces and torques.

Microgravity can make even simple tasks more difficult. For example, a person closing a drawer while standing on Earth simply plants their feet on the ground and pushes with their hands. If the drawer requires significant force and is causing them to tip backwards, they lean forward to apply some of their weight to the drawer. The first step for someone closing a drawer in microgravity is to find a place to secure their feet. Then, if the drawer requires significant force to close and they find themselves shifting backwards, they do not have the ability to lean in and use their weight to assist. Without a dedicated restraint in place, they must either counteract all forces and torques with their feet and ankles as a pivot point or devote a hand to stabilize and provide the extra force from another point.

Application of high forces is the most obvious place where restraint is required in microgravity, but restraint is needed even for very light applications of force. Actions as simple as typing on a keyboard can push an unrestrained crewmember up and away from the keyboard.

Typically, crew's instinct will be to restrain themselves with their feet as much as possible, as demonstrated by 20+ years of resident ISS crewmembers, leaving their hands free to manipulate objects and perform dexterous tasks. The preference for restraint using feet closely mimics how people prefer to restrain themselves on Earth, although this is accomplished quite differently in space. On Earth, gravity allows people to react to loads with the bottoms of their feet, while microgravity foot restraints rely on slipping the tops of feet underneath a restraint to counteract the tendency to float away. This uses different surfaces of the foot, but also different muscle groups that can take time to adapt to using.

8.1.2 Crew Mobility

While restraint in microgravity shares some basic principles with restraint on Earth, human mobility in microgravity is entirely transformed. On Earth, the body's default state is to be at rest, and only through the deliberate application of significant energy can we get and keep our body in motion. This makes feet and legs perfect for mobility because they can apply the consistently high forces needed for walking. There is also relatively little precision required on Earth since motion is naturally adjusted and arrested through gravity and friction.

In microgravity, however, the slightest of touches will initiate motion. This could be translation in any direction in 3D space, or rotation about any axis. Furthermore, induced motions will not stop until deliberately counteracted. This increased sensitivity of motion often requires more precision and control than feet are capable of providing, necessitating extensive use of hands.

In a typical microgravity translation, crew will start by using their hands to control orientation by pushing, pulling, or twisting around surfaces and handholds. Once in the desired direction of travel, hands or feet may be used to push off and initiate motion. While in motion, hands and feet are used to provide course corrections, and hands are typically used to initiate turns. At the end of translation, the crew must also arrest their motion, since this will not occur naturally. This is done with both hands and feet.

With enough time in space these translations become natural, but it takes time for newcomers to adapt. ISS first-time fliers as well as returning crew have reported adaptation periods that range from several days to weeks to learn how much energy to expend and how to control their momentum. All crew on board should be mindful in these early mission timeframes because there is an increased risk of injury or damage to hardware.

8.1.3 Hardware Restraint and Mobility

Up to this point we have discussed only the restraint and mobility of humans, but similar principles apply to every object in the crew's environment. On Earth when conducting science in a lab or maintenance in a garage, operators rely on gravity and ample table space to organize and contain parts and tools. But in microgravity an object placed on a flat surface by the crew will not stay in that position of its own accord and may float away. Crews often report items lost lor long periods of time after they are carried away by air currents inside the spacecraft. Conversely, hardware intended to be moved (especially if large or high mass) can be difficult to move in microgravity without sufficient grip or handles. Restraint and mobility of crew hardware can be just as important as the restraint and mobility of crewmembers themselves. It is similarly desirable for the restraint and mobility of hardware to be as hands-free and as effortless as possible.

8.2 HARDWARE CONSIDERATIONS

It is impossible to live and work in space without R&MA functionality that is interoperable across multiple operational and translation needs. Therefore, it is critical to design R&MA hardware and systems that support the crew's ability to safely complete mission objectives. The following sections provide R&MA design considerations based on previous long-duration human spaceflight crew feedback.

8.2.1 Placement and Reach

R&MA placement is the most important aspect of the overall R&MA system. Even the best R&MA hardware designs are useless if they cannot be mounted where they are needed. Interfaces that provide structural attachment of R&MA to the spacecraft must be appropriately located, configurable, easily accessible, and plentiful. The most frequently used structural R&MA interface in NASA spaceflight programs is seat track (Figure 8-1), so seat track will be used as a common reference point throughout this paper. But this should not discourage designers from exploring other possible alternatives.

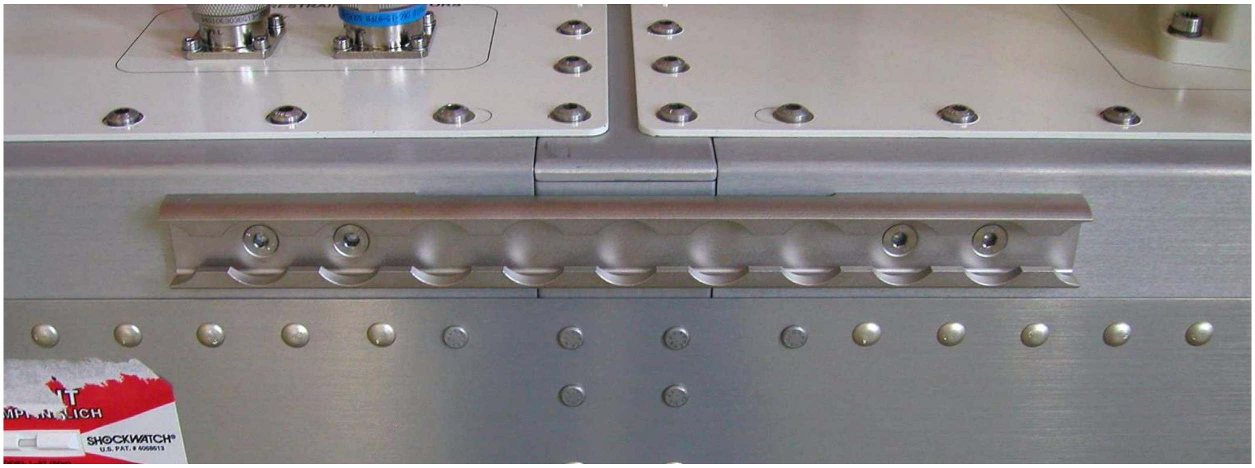

Figure 8-1. ISS Seat Track.

Seat track placement should eliminate “dead zones” where crew could be stranded without R&MA capability. The crew should also be capable of positioning their hardware anywhere within the habitable space, with reasonable topology configurations in mind.

Ensuring “continuous reach” offers a good minimum starting point, but it is beneficial to provide even more R&MA placement options than just this minimum. R&MA options are especially important to consider in high traffic areas like hatchways, along frequently used translation paths, locations that crew may need to turn 90 degrees during translation, or locations where crew will be stationary and conducting daily life or mission operations for any length of time.

It is impossible to determine before flight what the best R&MA configuration is, so the crew must be provided with enough interfaces to move R&MA hardware, with R&MA interfaces like seat track readily available in locations that meet their translation and operational needs. Over time, crews perfect their preferred R&MA setup and often avoid changing it further as they grow accustomed to R&MA being present in specific places as they instinctively move through the spacecraft.

8.2.2 Flexibility, Variety, and Interoperability

In addition to the placement of plentiful mounting interfaces, R&MA hardware design should offer variety and flexibility of use as much as possible. Throughout this section, a variety of unique R&MA hardware designs from the ISS will be discussed, but even this represents only a small subset of all the R&MA options available to the crew.

One of the most common examples of R&MA are handrails (Figure 8-2), which mount to seat track and act as a cornerstone of the R&MA system on the ISS. They come in a variety of lengths and, as the name implies, are intended to provide hand-guided mobility. Additionally, the design enables crew to slide their feet underneath and use them regularly as a foot restraint system. The handrail hardware flexibly provides the crew with both a mobility aid *and* a restraint function along its entire length, usable with hands *and* feet, which is a highly desirable feature.

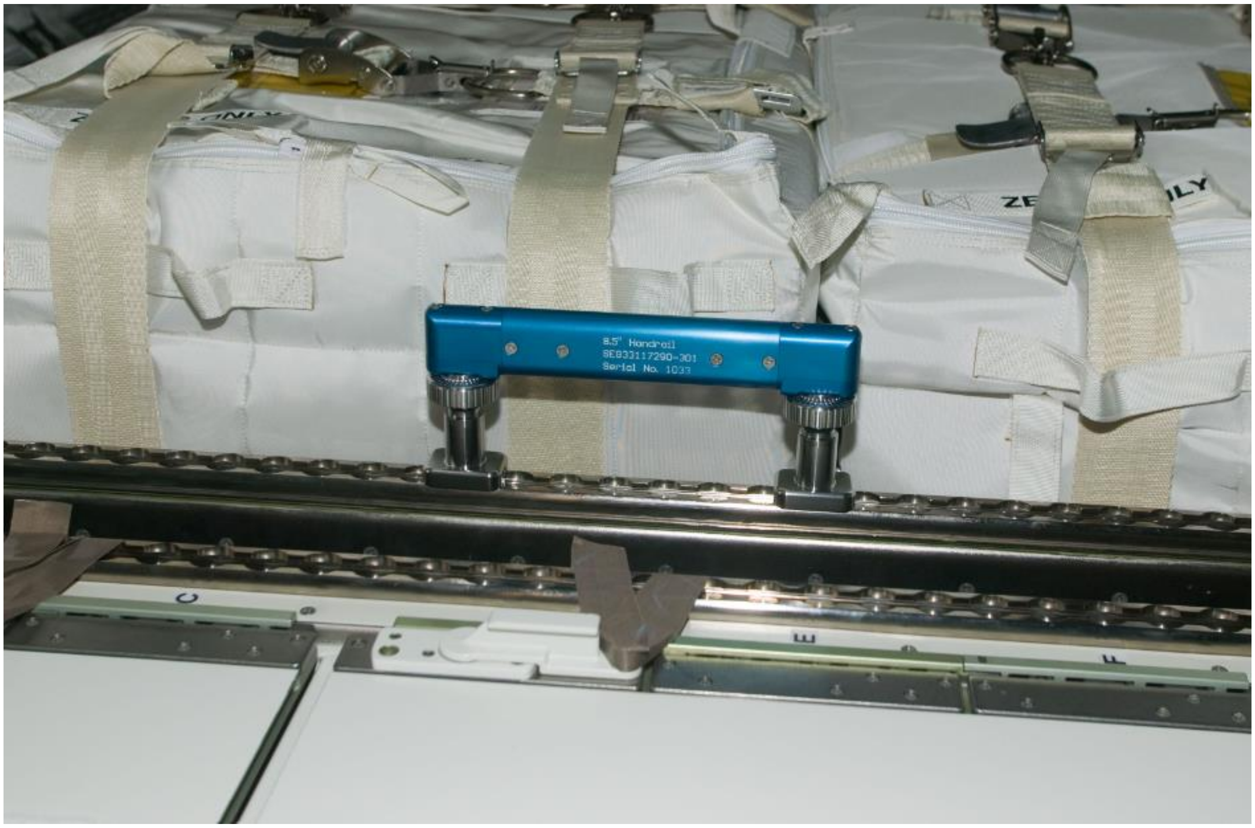

Figure 8-2. 8.5" Handrail Mounted to Seat Track.

It should be noted that handrails are constructed of bare metal that can be uncomfortable for long duration use. Some ISS crewmembers developed callouses on the tops of their feet over time. In places where crew stayed in one location for longer periods of time like Crew Quarters or at the Galley table, the crew modified handrails by padding them with soft goods to make them more comfortable footholds. In other places, the crew chose to install purpose-built foot restraints (Figure 8-3), such as at the toilet and at robotic workstations. R&MA should be configurable enough to support ergonomic working positions for differently sized crewmembers, especially at longer-duration workstations.

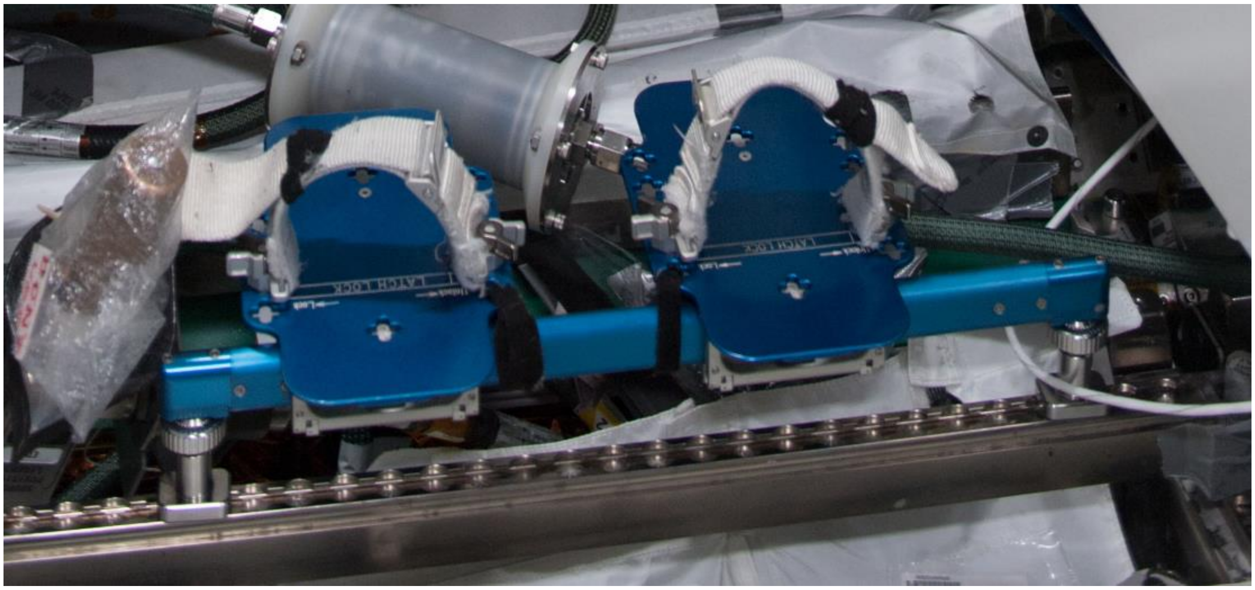

Figure 8-3. Long-Duration Foot Restraint Mounted to a Handrail.

As much as possible, R&MA attachment interfaces should be compatible, adaptable, and interoperable with one another. This can allow R&MA to stack together, reach further, and interact with more hardware. Clamps are a good example of a multipurpose and interoperable interface (Figure 8-4), which can effectively add seat track to areas that do not have any built in. Subsequent R&MA with seat track interfaces can then be stacked on top until a desired length is reached, greatly increasing crew's ability to mount hardware wherever desired in 3D space. On ISS, the crew took advantage of these features to mount things like cameras, which needed to reach all the way in the center of a module for a PAO event, or all the way to the back of hard-to-reach areas for views of maintenance activities.

Figure 8-4. ISS Handrail Clamp (left) and IP Clamp (right).

8.2.3 Ease of Manipulation

Easy and efficient R&MA manipulation for installation, adjustment, and use is ideal. The goal should be to minimize the time and effort standing between a crewmember and their desired translation path or restraint strategy. One-handed R&MA installation, adjustment, and removal is preferred wherever possible.

Adjustment of installed R&MA should also be as simple and capable as possible. Some of the crew's most-utilized restraint systems are those that allow 6 degrees of freedom articulation, yet easily rigidize to hold objects in place. Examples of such systems on ISS included the Multi Use Brackets and Flexible Brackets (Figure 8-5). One ideal feature of the Flexible Bracket was that crew could make it as long or as short as needed for any given task.

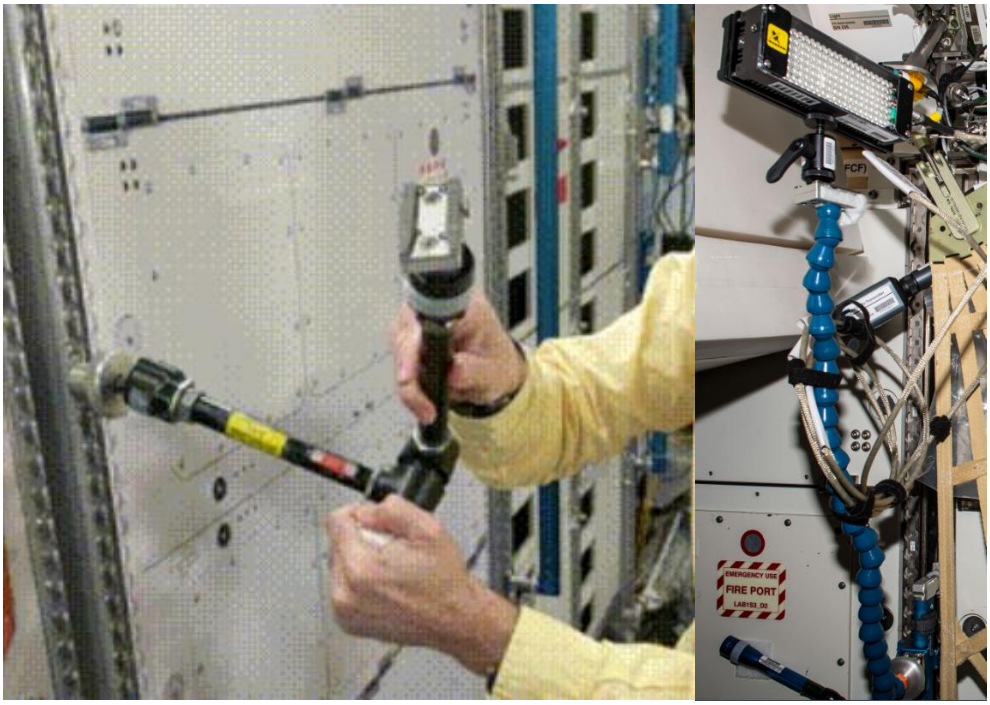

Figure 8-5. Multi Use Bracket (left) and Flexible Bracket (right).

An example of simple and easy to use restraint hardware, especially for stowing smaller handheld objects, is Velcro (Figure 8-6). Velcro was placed all over ISS and was consistently used and requested for use by all ISS crews. On hard surfaces it is affixed using adhesive, although this can leave a residue that is difficult to remove. This adhesive does *not* adhere well to soft goods, so Velcro is frequently sewn on these surfaces. Technical downsides of Velcro include degradation and contamination over time, as well as flammability concerns. An operational downside is that Velcro does not easily permit orientation changes of objects and is less effective at restraining larger hardware.

Figure 8-6. Velcro at Maintenance Work Area.

An example of a restraint typically utilized for large hardware is bungees, which were used extensively for managing stowage on ISS (Figure 8-7). Bungees rely on having readily available structural attach points. Carabiners are sometimes used in addition to bungees to tether objects to the bungee in case they slip out from underneath.

Figure 8-7. Cameras and Stowage Under Bungees.

Crewmembers also used things like Velcro and carabiners to attach hardware to their clothing, leaving their hands free. Many articles of clothing have Velcro or fabric loops built in for this purpose. This makes the restraint, translation, and availability of small to mid-sized objects much more convenient and augments the use of pockets.

8.2.4 Safety

There are some important safety considerations and lessons learned to keep in mind with some restraints and mobility aids. The best crew restraints keep crewmembers rigid and well secured, but it is also important that this be balanced with ease of release. Crew must be able to quickly release themselves from restraints in case of emergency.

Bungees are among the most used hardware restraints on ISS, but their elastic tension means they can spring free at high velocity when unhooked, which has the potential to result in serious injury. In some cases, non-elastic adjustable straps can substitute for bungees, but the crew finds them harder to use to apply tension.

When it comes to mobility, crew is able to move at very high speeds once acclimated to the microgravity environment, and high speeds can cause hazards. ISS crewmembers have reported that when using handrails to slow down from high speeds, the handrail gaps can create an entrapment hazard. Combined with high speeds, an entrapment could seriously injure the crew or damage hardware.

Finally, R&MA is typically rigid, and also tends to protrude some amount into the habitable volume. This makes it susceptible to being inadvertently bumped by the crew. R&MA should avoid the use of sharp angles that could injure crew when bumped. Particularly in larger habitable volumes where crew translation velocities may be higher, consideration should be given to padded, non-metallic, or flexible R&MA.

8.2.5 Unintended R&MA

Humans will subconsciously utilize whatever hardware is available to them as a R&MA. This is true even on Earth, where most of us have sat on stairs, tables, or other surfaces not actually designed for sitting. Similarly, we will instinctively grab at anything in our vicinity to keep ourselves from falling. The same is true in space, and therefore R&MA should be thought of as a hardware function; if something *appears* capable of functioning as a restraint or as a mobility aid, it likely will be used as such.

Hardware *not* intended to be a restraint *or* mobility aid may still be used as such if its design indicates it is functionally possible to do so. This is especially true if no better R&MA options are available in a particular area. For example, if there was a stretch of space along an ISS translation path that had no handrails, crew were forced to course correct using hatches, closeout panels, cables, hoses, or any other hardware available.

Similar things can happen if crew needs to work in an area without restraint hardware. On the ISS, a vacuum hose routed next to the Lab window offered an unintended handhold for photography, where no other handholds were available (Figure 8-8). Crew used it for this function, which resulted in a small atmosphere leak. A cover was subsequently built for this hose to protect it from being used as a handhold in future.

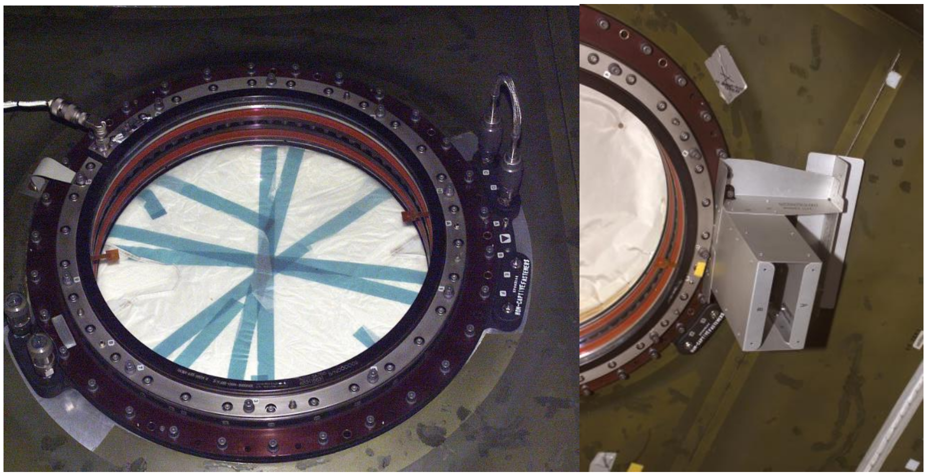

Figure 8-8. Vacuum Vent Hose on Lab Window Exposed (left) and Covered (right).

Designing hardware so that it is difficult to inadvertently be used as a handhold is a good start but is difficult to do and not foolproof. Therefore, hardware should *also* be designed to either withstand inadvertent loads, be covered with closeout panels that can withstand loads, or both. This helps to account for unplanned usage as R&MA, which any hardware is susceptible to.

8.3 OPERATIONAL CONSIDERATIONS

8.3.1 R&MA Inventory Management

Because R&MA is ideally crew managed (i.e., deployed and moved by the crew at will to support their needs), it is particularly difficult to track. This can make it difficult to depend on finding specific hardware when needed. For example, procedures on the ISS regularly called for the use of Multi Use Brackets to restrain hardware, but personnel on the ground may not have actually known if or where a Multi Use Bracket was available. This led to extra crew time spent searching for a free unit, or subsequent requests for hardware audits. There are some possible operational workarounds that can protect crew's ability to self-manage R&MA.

1. Reserve a small supply of R&MA to be used outside of crew's nominal needs to support a payload or activity for a designated time. Crew can grab from this reserve when needed without relocating their crew-deployed R&MA and possibly disrupting their instinctive translation and restraint patterns.

2. Allow crew to determine which deployed R&MA will be dedicated to a particular activity. This pulls R&MA from the nominal locations, but it gives crew the flexibility to determine which of the R&MA will create the least impact to daily operations. It works well as long as the requirement for dedicated R&MA is minimal and for a short duration. Additionally, crew must be given additional time to locate and make available the necessary R&MA as doing so will require hardware reconfiguration.

3. For especially specific, long-duration, or high-quantity R&MA needs outside of nominal use, it may be best to have the requestor send up their own R&MA. That ensures that exactly what they need, when they need it, will be available. The downside to this approach is an increase in upmass, and a steady accumulation of one-time-use hardware that contributes to clutter and stowage problems.

8.3.2 R&MA Considerations for Operations Planning

When planning high force or high torque tasks, the ground must consider if and how the crew will be able to restrain themselves for the task. Ground personnel can perform worksite analysis and offer suggestions, but in the end, it is typically the crewmember who determines which strategy works best for them. Sometimes, if sufficient R&MA options are not available, a second crewmember may be required for an extra set of hands.

8.3.3 Manifesting of Replacements

Designers should be aware of the frequency of use of R&MA and strive for simpler and more robust designs that can tolerate abuse. But even keeping this in mind, R&MA may loosen over time and require refurbishment or replacement. It can be difficult to tell when this is required, in part due to lack of R&MA inventory management. Consideration should be given to R&MA sustainment plans, and these plans may require audits or regular reports from the crew. If R&MA is designed to be refurbished, it is advantageous to enable refurbishment in space using common tools.

9.0 GENERAL HABITABILITY

9.1 OVERVIEW

This section addresses habitability considerations that are either too broad or too specific to fit neatly into one of the earlier sections. Common considerations are those that impact every aspect of habitability. Unique considerations apply to specific hardware.

9.2 COMMON HABITABILITY CONSIDERATIONS

9.2.1 Separate Functional Areas

Create functional areas (e.g., work area, dining area, hygiene area, etc.) within the habitable volume wherever possible. This can be accomplished by collocating like hardware, but also by separating hardware with dissimilar functions. Consider the tasks that will be completed in each area to ensure sufficient volume for the number of crew inhabiting the area at any given time.

Examples:

a. Collocate like hardware: Create a galley space for all food preparation and dining hardware; a workspace with tools and a workbench; a sleep/personal space with sleep compartments, crew personal items, dimmable lighting, soundproofing; etc.

b. Keep some distance between work and rest/recreational areas: Separate the workbench physically from the sleep area.

c. Separate high-traffic areas: The galley will be used frequently during the day, as will the exercise area. Avoid placing them close together.

d. Separate “dirty” functions from “clean” functions: Keep the galley and sleep areas, which crew will strongly desire to keep clean; separate from exercise, toilet, and trash stowage areas.

   Note: Hygiene does not fit neatly into either of these designations. Crewmembers have expressed that it is unacceptable to conduct hygiene in the dirty areas, but it is also important to keep hygiene products away from the clean galley and sleep areas. See more about the specific design considerations for the hygiene area in the *Hygiene* Section of this paper.

9.2.2 Hardware Design Considerations

Habitability hardware and spaces should be readily available. Habitability needs cannot typically be scheduled to occur only at certain times during the day. Crew will dine when they are hungry; go to the bathroom as needed; and change clothes in their Crew Quarters multiple times for exercise, public affairs events, or sleep. Hardware and related supplies that meet habitability needs should always be available for immediate and unscheduled use at crew discretion.

Habitability hardware should be intuitive. Crew should be able to use habitability hardware with little to no instruction and without written procedures. They will execute complex, technical procedures during the workday and should be accommodated with intuitive design for the hardware they will repeatedly interact with every day. Some ways to optimize user interface are to:

a. Clearly label switches and buttons.

b. Use colored lights or LED displays to indicate status.

c. Minimize the number of steps crew must execute. It should not take five switch-throws to dispense water into a drink bag, for example.

It is acceptable for habitability hardware to require some familiarity training before first use. Once trained, however, a crewmember should be able to independently operate habitability hardware using just the signatures provided by the hardware itself.

Habitability hardware should be easily maintainable. Crew will need to use habitability hardware all day, every day. Downtime to troubleshoot or repair it can have a significant impact to the timeline but will also impact crew morale. When habitability hardware breaks, it quickly becomes the crew’s priority to fix it as soon as possible, even if it means delaying other scheduled tasks. Planning for failures will minimize hardware downtime and have the least impact to crew habitability.

a. For hardware with known lifetime limits, keep spare parts on the vehicle. Have repair procedures already written and ready for execution.

b. Be familiar with possible failures (even if unlikely). Have troubleshooting and repair procedures ready for execution.

c. Make spare parts modular whenever possible to simplify removal and replacement.

d. Design replaceable parts to be easily removed and installed with minimal tools.

9.2.3 Carbon Dioxide Scrubbing

Much has been documented about CO2 management in spaceflight. This paper does not address safe versus unsafe CO2 levels or specific integrated hardware solutions. However, exposure to CO2 has a negative effect on human health and performance, so will be addressed at a high level.

On Earth, variations in temperature, pressure, and gravity in our atmosphere cause air to mix naturally. This prevents inhaling increased amount of CO2 due to build-up around the face. In space, that mixing does not happen naturally and, without a motive force, CO2 pockets can form. Exposure to CO2 negatively affects crew health.

Symptoms include fatigue, irritability, headaches, congestion, short-term memory issues, anxiety, and sleep disturbance, among others. Therefore, maintaining adequate airflow and CO2 removal throughout the spacecraft volume is critical to ensuring a safe, successful mission and crew quality of life. In addition to robust airflow and CO2 scrubbing, CO2 levels should be consistently and robustly evaluated and monitored to ensure effective mitigation.

Consider areas where crew will gather (like the galley) and enclosed areas (like the sleep compartments), where CO2 removal will be particularly imperative. It is important to provide portable fans that crewmembers can deploy as desired. On ISS, crewmembers frequently used portable fans in exercise areas and in their sleep compartments, both areas where CO2 accumulated. They also deployed fans when working in one area for a for a significant period of time or when working in an area with stowage or walls that may have restricted airflow to avoid high CO2 concentration.

There are many publicly available sources regarding human spaceflight CO2 concerns and removal methods. Citations to publicly available sources regarding CO2 concerns and removal methods are listed at the end of this section.

9.3 UNIQUE HABITABILITY CONSIDERATIONS

9.3.1 Windows

The windows on ISS allowed for situational awareness of the exterior structure as well as events occurring on the exterior of the space station, such as vehicles approaching or departing, inspection of exterior hardware, or EVA crewmembers performing maintenance tasks. They were also vital for providing photography and video opportunities. But the windows were additionally a favorite location for crewmembers. The importance of windows to crew morale cannot be overstated. Having time to look out of the windows impacts crew rest and relaxation, which in turn contributes to efficiency and overall wellbeing. Windows should be a part of any spacecraft design and should be available for crew use with as few restrictions as possible.

Window optical quality is important, especially if windows will be used for photography. The human eye can see through a lower quality window than a camera can. Additionally, efforts should be made to protect the window optical quality and structural integrity. Citations of publicly available sources regarding window design are listed at the end of this section.

9.3.2 Interior Lighting

9.3.2.1 Installed Lighting

Lighting should provide variable color (cool/warm) and intensity (bright/dim) and should be controllable by both the ground and onboard crew.

The ISS used variable lighting to mimic Earth’s day and night cycles, which encouraged healthy sleep habits and helped the crew adjust to sleep schedule modifications.

During the workday on ISS, lights were nominally set to a bright setting with a cool tone to simulate daylight on Earth. In the crew evening, lights were dimmed and set to a warmer tone to simulate dusk. This cycle supported the crew circadian rhythm. Additionally, light should come from above, like sunlight.

Interior lighting should be manually adjustable per crew preference so that the optimal light level and color can be selected at any given time. Both ground and crew should have the ability to power on or off lights, to adjust light color and intensity, and to synchronize all lights to the same mode. System controls allow crew and ground to control all lights within a module or vehicle. Local controls are also important to allow crew and ground to adjust individual lights. This provides adjustment capability at a particular worksite or for a particular task.

It is also important to minimize glare from installed lighting. Glare can negatively affect crew vision but is also a source of crew irritation and fatigue. Multiple things affect glare, like bulb choice and light direction. Surface finish (e.g., paint colors, reflective properties) can also contribute to glare and should be considered in spacecraft design.

9.3.2.2 Portable Lighting

Portable lighting is important to assist crew working in areas not sufficiently illuminated by the installed lighting or when working with small components. Examples include behind panels and in areas congested with power/data cables.

Consider how portable lights will be powered and mounted. Ideally, portable lights will not require a power cord during use as it will limit the range of use. Battery powered lights and lights that can be charged prior to use will provide more flexibility. Flashlights work for many needs, but hands-free lighting options for crew to use while they are working should also be provided. Headlamps are a good option, as are small lights that can be mounted to brackets or surfaces and aimed at the work area.

Some portable lights provided for ISS crew:

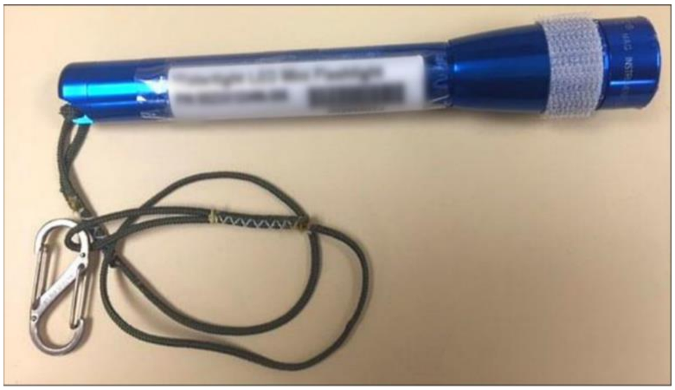

Figure 9-1. Mini Flashlight with Velcro and Tether.

Figure 9-2. Work Light Attached to a Flexible Bracket.

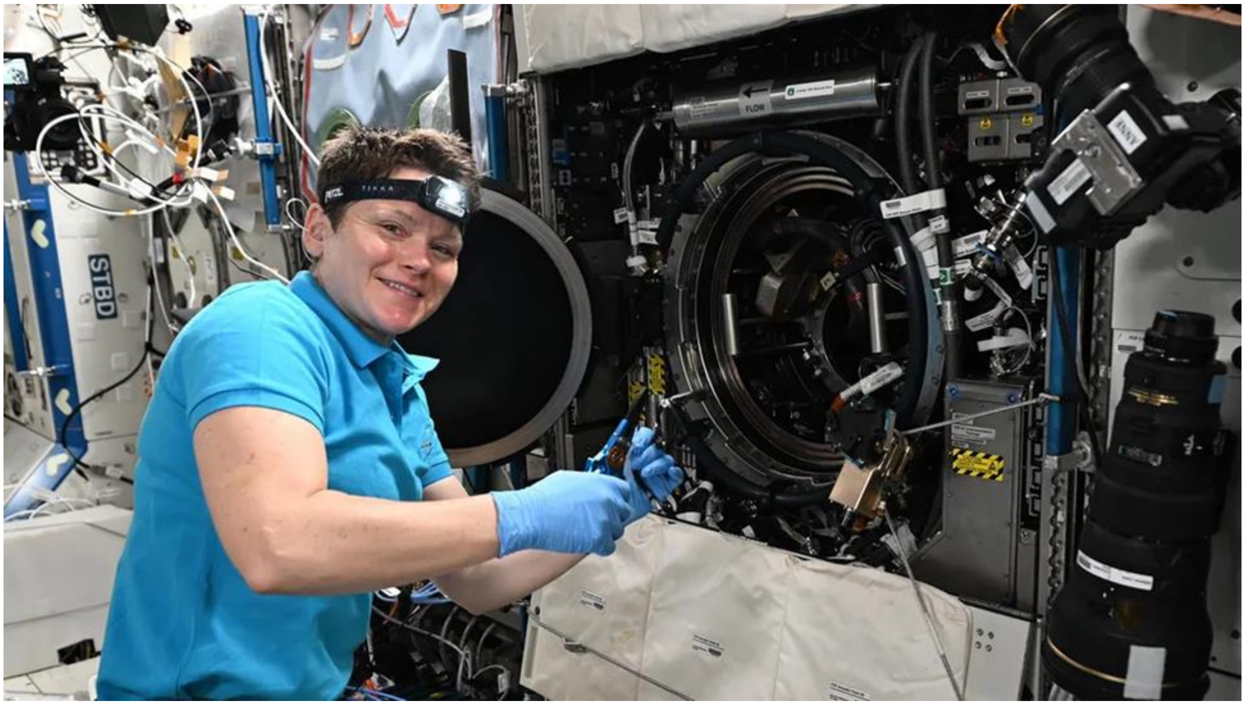

Figure 9-3. ISS Crewmember Wearing a Headlamp.

Additional resources

Carbon Dioxide Scrubbing

- “Overview of Carbon Dioxide Control Issues During International Space Station/Space Shuttle Joint Docked Operations,” C. Matty, 40th International Conference on Environmental Systems, 2010: https://arc.aiaa.org/doi/pdf/10.2514/6.2010-6251

- “Chronic Exposure to Moderately Elevated CO2 During Long-Duration Space Flight,” P.D. Cronyn, S. Watkins, D.J. Alexander, 2012: https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/N20120006045.xhtml

- “Carbon Dioxide (CO2),” NASA Office of the Chief Health & Medical Officer (OCHMO), NASA Technical Brief, 2023: https://www.nasa.gov/wp-content/uploads/2023/12/ochmo-tb-004-carbon-dioxide.pdf

- “Carbon Dioxide Physiological Training at NASA,” J. Law, M. Young, D. Alexander, S. Mason, M. Wear, C. Mendez, D. Stanley, V. Meyers Ryder, M. Van Baalen, Aerospace Medicine and Human Performance, 2017: https://asma.kglmeridian.com/meridian/asma/published/rest/pdf-watermark/v1/journals/amhp/88/10/article-p897.pdf/watermark-pdf/

- “Allowable Exposure Limits for Carbon Dioxide During Extravehicular Activity,” A. Seter, NASA Technical Memorandum, 1993: https://ntrs.nasa.gov/api/citations/19940006903/downloads/19940006903.pdf

Windows

Conference and publicly available technical papers:

- “The ISS Eye on the Universe: The Verification of ISS Cupola Window Glass,” L. Estes, World Space Congress, 2002, IAC-02-T.P.05.

- “Identification, Sourcing, and Prevention of Orbiter Window Haze,” L. Estes, Earth and Space 2004 Conference, 2004.

- “Engineering of Windows for the International Space Station,” L.R. Estes and K.S. Edelstein, The 9th ASCE Aerospace Division International Conference on Engineering, Construction and Operations in Challenging Environments (Earth & Space), 2004.

- “Orbiter Window Hypervelocity Impact (HVI) Strength Evaluation,” L. Estes, 35th International Conference and Exposition on Advanced Ceramics and Composites (ICACC’11), 2011.

- “Orbiter Window Hazing,” L. Estes, AIAA Space 2011 Conference and Exposition.

- “Examination of Relationship between Photonic Signatures and Fracture Strength of Fused Silica Used in Shuttle Windows,” W.T. Yost, K.E. Cramer, L.R. Estes, J.A. Salem, J. Lankford, and J. Lesniak, NASA TP-2011-217322.

- “Arc-Jet Testing Report for Polycarbonate and Acrylic Window Materials,” L. Estes, JSC 66691, 2013. “Residual Strength of Hypervelocity Impacted Silica,” J. Salem, J. McMahon, and L. Estes, ICACC, Feb 2021.

Multimedia:

- APPEL Podcast: https://appel.nasa.gov/podcast/episode-59-spacecraft-window-design/

- Window Material Database, https://winmd.appdat.jsc.nasa.gov/index.cfm

Technical Requirements Documents for Spacecraft Windows:

- “Strength Design and Verification Criteria for Glass, Ceramics, and Windows in Human Space Flight Applications,” NASA-STD-5018. 2011, Primary author, L. R. Estes.

- JSC 66320, Optical Property Requirements For Glasses, Ceramics And Plastics In Spacecraft Window Systems, Rev B, 10/01/21.

10.0 CONCLUSION

Human beings can live and work successfully in stressful environments, including the microgravity environment of space, when physical and psychological needs are met. The easier it is to meet basic human needs, the better crewmembers can focus on mission objectives. Conversely, insufficient habitability accommodations negatively impact the crew both physically and mentally, in turn impacting crew efficiency – especially during long-duration missions.

Spacecraft design that incorporates the recommendations in this paper will help to ensure mission success by protecting the health and wellbeing of the crew, and may prevent costly modifications to the vehicle once in space.

APPENDIX A
ACRONYMS AND ABBREVIATIONS

BCR	Barcode Reader
CO2	Carbon Dioxide
COTS	Commercial Off the Shelf
ECLSS	Environmental Control and Life Support System
EVA	Extravehicular Activity
FOD	Foreign Object Debris
IMOC	Integrated Mission Operations Contract
IMS	Inventory Management System
IMV	Inter-Module Ventilation
ISS	International Space Station
IVA	Intravehicular Activity
JSC	Johnson Space Center
LED	Light Emitting Diode
mL	Milliliter
NHV	Net Habitable Volume
PAO	Public Affairs Office
PMM	Permanent Multipurpose Module
PPE	Personal Protective Equipment
R&MA	Restraints & Mobility Aids
RFID	Radio Frequency Identification
RSR	Resupply Stowage Racks
WMS	Waste Management System
ZSR	Zero-G Stowage Racks