

Improvements to On-Orbit Sleeping Accommodations

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United States On-Orbit Segment (USOS) crew members aboard the International Space Station (ISS) are each furnished with a Crew Quarters that serves as their personal private space for the duration of their expedition. Within these quarters, crew members use sleeping bags to provide a comfortable environment that is conducive to sleeping in microgravity. Microgravity presents unique challenges to obtaining good sleep. Sleep position preferences which are influenced by gravity are disturbed when the feeling is absent while other environmental factors prevent the familiar feeling of lying in bed. NASA developed a new US Sleeping Bag for USOS crew members launching aboard United States Crewed Vehicles (USCVs), using this opportunity to improve upon the current sleeping bag design based on lessons learned from years of living and working in space. The US Sleeping Bag design was based on the current sleeping bag's design with enhancements to key features based on feedback from crew members and sleep study experts at the Johnson Space Center and the Ames Research Center. Key areas of improvement include facilitating thermal comfort in the warm Crew Quarters environment, ease of maintenance when replacing the inner lining, allowing for maximum versatility for adjustment to crew preference, and adding features for additional functionality such as accommodations for a pillow. Two US Sleeping Bags have flown aboard the ISS to date, utilized by veteran crew members who have experience with the existing sleeping bags and have provided feedback and comparisons for assessment. Enabling good sleep is essential for crew member health and productivity, especially in longer duration expeditions. This paper will detail the challenges with sleeping in microgravity and the enhancements made in development of the US Sleeping Bag to provide a better on-orbit sleep environment.

Nomenclature

°C	=	degrees Celsius
COTS	=	commercial off-the-shelf
CQ	=	Crew Quarters
dB	=	decibel
°F	=	degrees Fahrenheit
ISS	=	International Space Station
JSC	=	Johnson Space Center
USCV	=	United States Crewed Vehicle
USOS	=	United States On-Orbit Segment

I. Introduction

SLEEPING in space presents unique challenges. Many of the aspects that lead to good sleep in a 1g environment are no longer present in a microgravity environment. Poor sleep can be a hindrance to work performed aboard the International Space Station (ISS). Learning how to provide a good sleep environment for crew members is currently a subject of study in order to improve crew member health and performance. Better sleep is expected to lead to more productive crew members for longer periods of time, which is especially of importance to long-duration exploration missions.

Sleeping in microgravity presents additional challenges.¹ The environments of vehicles such as the ISS and Space Shuttle are noisy; the ISS open cabin can reach a constant noise level of 80 dB. Old sleep restraint systems

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included metallic components that would rattle intermittently. One-quarter of crew members have reported that they use ear plugs to reduce noise levels while sleeping. During Shuttle missions, approximately one-third of crew members reported that the most important part of the body to be concerned with during sleep is the head because it can nod, tilt, and twist during sleep which can wake the crew members and create soreness in the neck the following day. Sleep study scientists at the Johnson Space Center have determined that the ability to rotate the head without tilting while restrained for sleep is the most ideal scenario. In microgravity, there is no familiar feeling of pressure against the body as one would experience in bed on Earth. This can be roughly simulated in microgravity via restraints holding the crew member against a solid surface. However, crew members tend not to like internal restraints since they restrict movement too much. The ability to readjust position during sleep is important and too much restraint can interfere with this. Restraints external to the sleep accommodations with some amount of elasticity, such as bungee cables, are preferred for this purpose. Another sleep issue experienced in microgravity is the inability to stretch muscles for long periods of time. Without the assistance of gravity the body will return to a neutral position unless the person is actively working to keep the position. A sleep accommodation designed for use in microgravity must take these into consideration if the occupant is to achieve good sleep.

United States On-Orbit Segment (USOS) crew members aboard the ISS make use of sleeping bags inside their Crew Quarters (CQ). The sleeping bags provide a soft and warm environment and also serve to safely restrain the crew member to the wall of their CQ. In this way, the crew member can use the sleeping bag not only for sleep (both nighttime and daytime naps) but also as a general restraint during waking hours while working or relaxing inside the CQ. Currently, USOS crew members launching aboard the Soyuz vehicle are furnished with Russian-developed sleeping bags for use during their expedition. These sleeping bags are provided as part of the agreement to launch USOS crew aboard a Russian vehicle. These sleeping bags are generally well-received by the crew with minor comments, although the warmer environment inside the CQ causes some crew members to comment that the sleeping bag is too warm for the CQ environment. Programmatically, in 2015 a need was identified for a NASA-developed sleep system to take the place of the Russian-developed sleeping bags once USOS crew members began launching aboard United States Crew Vehicles (USCVs). The ISS Program thus directed the development of a new sleeping bag for use by USOS crew members launching aboard USCVs. Due to funding limitations, the new sleeping bag was to be based off of the existing sleeping bag design with minor-to-moderate improvements as funding and schedule allowed. This led to the creation of the US Sleeping Bag.

II. US Sleeping Bag Design Improvements

The US Sleeping Bag (Figure 1) consists of three main components: the sleeping bag shell, a replaceable liner installed inside the sleeping bag shell, and a set of eight ties used to fasten the sleeping bag to a hard surface. The primary purpose of the shell is to provide structure to the sleeping bag. The sleeping bag shell consists of an outer non-flammable material, insulation/padding, and a softer inner lining. The primary purpose of the liner is to provide a soft material against the crew member and to facilitate a hygienic environment by periodic replacement with a new, clean liner. The liner consists of a thin material that attaches to the sleeping bag shell via Velcro. The purpose of the ties is to attach the sleeping bag to the sleep wall of the CQ. The ties are made of a non-flammable cord material and bear a resemblance to shoelace strings. The US Sleeping Bag measures approximately 83 in x 27 in x 1 in (211 cm x 69 cm x 3 cm) and weighs approximately 7 lbs (3 kg).

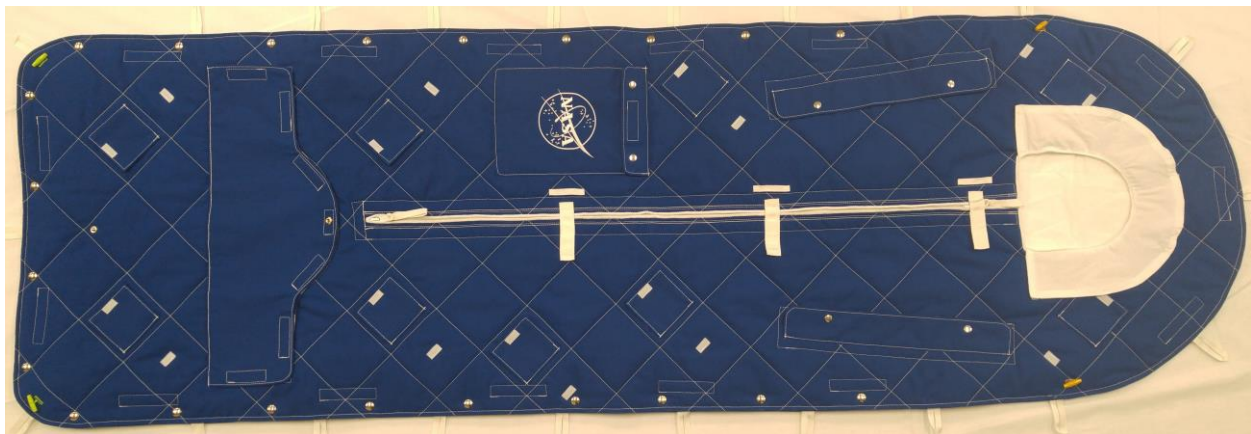


Figure 1. US Sleeping Bag.

Several aspects of the existing Russian sleeping bag design were considered for improvement. Crew comments were solicited to identify areas of the existing sleeping bag system that could be improved based on their experience with the sleeping bags aboard the ISS. A common comment received is that the sleeping bag is too warm for the CQ environment. Another mutual comment is that the sleeping bag liners, analogous to bed sheets on typical bed, were time consuming and difficult to replace. This led to hygiene concerns if the liners were not replaced, as they would continue to soil without cleaning. Above all, the main comment received was that the sleeping bag should be as versatile as possible since individual sleep preferences vary significantly. Additionally, during the development of the US Sleeping Bag it was also decided that the sleeping bag should also fit a wide range of crew members. Typically, this is designed for the 5th percentile Japanese female up to the 95th percentile American male as defined by the International Space Station Flight Crew Integration Standard.² Lastly, minor additional functionality was added to the US Sleeping Bag design in order to improve the user experience.

A. Materials Selection and Thermal Comfort

The temperature inside the ISS is fairly warm, and the Crew Quarters lacking active cooling are typically even warmer. This presents a challenge with sleeping bags used aboard the ISS. Initially, a feasibility study was performed of commercial off-the-shelf (COTS) sleeping bag options to determine if they would be viable replacements for the existing sleeping bag system. Several types of sleeping bags were examined. All types contained downsides which made them unsuitable for use in the CQs. Primarily, the concerns were that the COTS sleeping bags were constructed of flammable material, the insulating material in many sleeping bags are common allergens, and most COTS sleeping bags are designed for environments much colder than those found in the CQ which can reach close to 80°F (27°C). Additionally, sleep temperature preferences can vary dramatically from person to person¹ and some CQs are warmer than others, being located further from the ISS air cooling system.³ The US Sleeping Bag needed to accommodate this generally-warmer environment while allowing for variability to accommodate a wider range of occupants.

During initial development of the US Sleeping Bag, a series of materials and material layouts were considered to construct both the sleeping bag and the liner. Project restrictions limited the number of selectable materials to those already approved for use aboard the ISS or those which could be quickly approved in flight configuration (e.g., flammable materials can be approved but only when enclosed by non-flammable materials). Externally, only a non-flammable material would be approved due to the considerable surface area of the sleeping bag and potential flammability concerns. Nomex was the only feasible material. However, in moderate-fidelity benchtop thermal testing it was found that this material is a good thermal insulator. Additional materials were considered for the sleeping bag insulation and inner lining. Several layouts were considered by the JSC Crew Office and preference was shown towards the layout with tight-weave Nomex exterior, a synthetic fiber thermal insulator, and elastic Nomex inner liner for occupant comfort. This layout was chosen based on a combination of the softness of the inner lining material, non-allergenic properties of the insulator, and rigidity of the material layout. A cotton bastiste material was chosen for the replaceable liner due to a combination of its softness and breathability, helping to reduce occupant temperature inside the sleeping bag. Although flammable, the majority of the liner is contained within the non-flammable sleeping bag shell. An anti-microbial material was considered for both the sleeping bag shell and replaceable liner. However, the material was not breathable and, for use aboard the ISS, it was determined to be more efficient to simply throw away soiled, disposable liners. Overall, the materials selection was determined to be more comfortable than the existing sleeping bag system with an approximately similar thermal insulating profile.

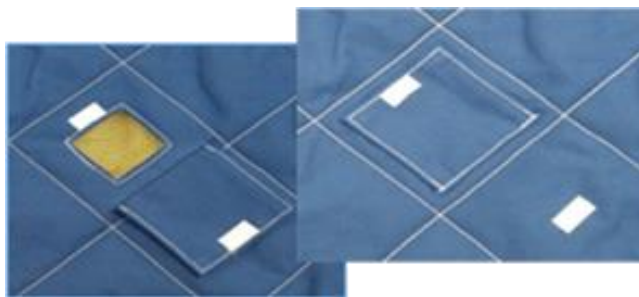


Figure 2. Vents with flap covers.

To help cool the US Sleeping Bag occupant, design changes were made to the vents. The existing sleeping bag system contained a number of vents on the front and back of the sleeping bag. These small, diamond shaped vents cut out of the exterior Nomex were covered by multiple layers of cotton. The US Sleeping Bag increased the total number of vents, replaced the cotton material with loose polyester netting material to allow better air flow, and increased the size of the vents to 4 in² – the maximum allowable for a contiguous flammable material aboard the ISS (Figure 2). In the event that

the occupant desired a warmer sleeping bag, covers/flaps made of two layers of Nomex were provided for each vent. Due to the thermal insulating properties of the Nomex, these covers should provide good insulation when fastened closed.

Other ventilation options were added to the US Sleeping Bag (Figure 3). The entry zipper along the front of the sleeping bag was outfitted with two zipper pulls. This allows the occupant to create their own larger “vent” along the front of the sleeping bag without fully opening the bag. Velcro tabs were added alongside the entry zipper for a similar purpose – the zipper can be fully open but Velcro tabs fastened to keep the sleeping bag in place around the occupant while allowing ventilation directly from the occupant and past the liner and sleeping bag. The vent at the bottom of the sleeping bag was enlarged and also raised to accommodate shorter crew members, allowing them to reach and better utilize that vent.

Although the thermal insulating properties of the US Sleeping Bag were limited by project restrictions and available materials, efforts were made to increase the ventilation capabilities of the sleeping bag and provide flexibility to crew members. Occupants can choose one of several types of ventilation to meet their preference. When inside the Crew Quarters, ventilation provided by the CQ will help to cool the occupants utilizing one or more of these ventilation options.

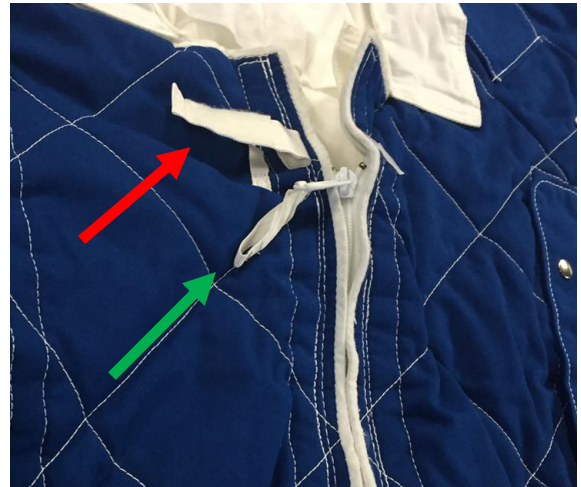


Figure 3. Main entry zipper with double pull (green arrow) and Velcro tab (red arrow).

B. Ease of Maintenance

Effort was made to update the design to make removal and replacement of the liner easier. Based on feedback from the crew, liners for the US Sleeping Bag (Figure 4) are intended to be replaceable every 30 days to help maintain cleanliness and hygiene. The liners would be stowed in a common pantry and periodically pulled for



Figure 4. US Sleeping Bag replaceable liner.

installation into a sleeping bag. The common complaint with the existing design is that the liner attached to the sleeping bag with Velcro surrounding the entire perimeter of the liner. This caused issues when attempting to align a new liner within the sleeping bag. Velcro would catch adjacent sections, and any slack or misalignment on one end translated the length of the sleeping bag causing misalignment with openings for arms and legs. Two design changes were implemented in the US Sleeping Bag to help address this issue: reduced Velcro and colored alignment toggles.

The amount of Velcro along the perimeter of both the liner and the sleeping bag was reduced in the US Sleeping Bag. This change was made in an attempt to reduce the “catching” issue during installation of the liner. Approximately two-thirds of the Velcro along the perimeters of both the liner and the sleeping bag was eliminated. This change reduced the occurrence of “catching” of Velcro during installation. Ground tests and demonstrations showed that as long as the Velcro is properly aligned, this amount of Velcro is sufficient to hold the liner in place while the sleeping bag is occupied.

To assist with alignment of the liner during installation, colored toggles were added to key locations on the liner (Figure 5). These locations are on the front of the liner near the head and on the front and back of the liner near the feet. The toggle colors – white, copper, and green – are installed through holes in the sleeping bag outlined with color-matching thread for easier visual confirmation of correct placement. Consideration of toggle color was based on color restrictions aboard the ISS (e.g. yellow indicates caution, red indicates warning) as well as potential distractions to the crew member. The intent of the colored toggles and thread is to facilitate easier visual indication of the orientation of the liner prior to installation. The toggles themselves are intended to be installed into the sleeping bag first. In doing so, the liner is fully stretched along the length of the sleeping bag, properly aligning the Velcro strips between the liner and the sleeping bag. Completing the installation along the perimeter is then a simple matter of pressing the Velcro strip pairs together. The colored toggles also serve as a visual indicator of the orientation of the liner prior to installation. The liner material is thin with several cutouts and can easily become tangled and difficult to manage prior to sleeping bag installation in a microgravity environment.

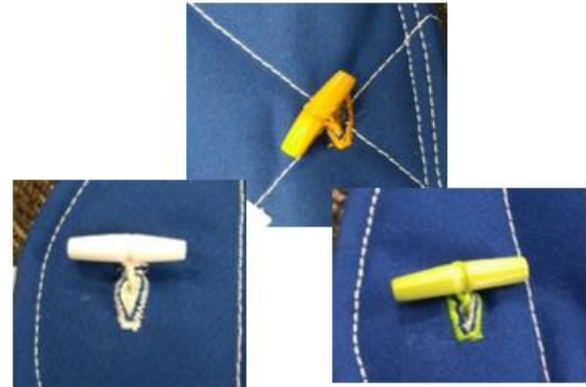


Figure 5. Replaceable liner's colored toggles with sleeping bag's matching thread.

Timed installation tests were conducted on a US Sleeping Bag prototype with a crew member and crew representative. In both cases, installation of the liner was found to be slightly faster with the design changes. Hindering the installation is the fact that the liner material is very thin and with the many openings/holes it can quickly become entangled in itself or the sleeping bag. Once the toggles were installed the installation of the perimeter and foot openings were quick. Alignment and installation of the Velcro around the arm openings and front zipper, as well as threading the internal straps through the liner, were performed slightly faster or the same speed as a liner without the design changes.

C. Allow for Maximum Versatility

Potentially the most important aspect of any sleeping accommodations is that it be versatile/adjustable to crew preference. Individual sleep preferences can vary considerably from person to person and the sleeping accommodations must be able to facilitate good sleep in any number of potential configurations. Features designed for versatility must also take into account the potential body size differences between crew members, including in height, width, and limb length.

One major change was the addition of a gusset along the majority of the sleeping bag's perimeter, allowing the sleeping bag to be expanded to add volume if needed (Figure 6). This feature, similar to the expandable gusset on a suitcase, allows for larger crew members to gain more space in their sleeping bag without feeling constricted. A comment received on the existing sleeping bag system was that some crew members would cut slits into the sides of the sleeping bag in order to make it more spacious. The gusset allows the sleeping bag to expand without requiring modifications to the structure. A series of snaps along the perimeter can be fastened or unfastened as desired to create space in specific user-specific areas of the sleep bag. For example, the area at the feet can be expanded to give more room to adjust foot position without being constricted, or the area around the torso can be expanded to provide a looser restraint. The gusset also allows for crew members to sleep with knees raised, which is a somewhat common sleeping position in microgravity, while keeping the sleeping bag tied to the wall. The gusset can also remain closed if desired, which may be the case for smaller crew members who do not wish to have the extra volume. During development of the US Sleeping Bag, crew evaluations were performed and this feature was well received, particularly by larger crew members.



Figure 6. Expandable gusset.

The existing sleeping bag system contained three internal straps around the upper torso, lower torso, and thighs to restrain the crew member to the back of the

sleeping bag. The feel of this restraint is intended to help simulate the feel of sleeping in a 1g environment, with pressure against the occupant's back. During development of the US Sleeping Bag in crew evaluations it was noted that the straps were uncomfortable and an annoyance to use due to the buckle design, and were often cut out of the sleeping bag completely. Some crew members however did use this feature so it was decided to leave the internal straps in the sleeping bag but make some modifications to their design. A new buckle was chosen that was larger in order to more easily loop through and fasten the straps. The strap itself was widened and the material changed to a softer weave of Nylon webbing so that it was more comfortable against the occupant. The bottom strap's position in the sleeping bag was also lowered slightly since it was noted during crew evaluations that the new position would



Figure 7. Face cutout in US Sleeping Bag – common point for sleeping bag occupants.

allow a crew member to raise their knees and then loop the strap around the knees to keep them in place during sleep. Although the internal strap feature seems to elicit a wider range of impressions from crew members, it is hoped that the modifications will allow them to become useful to a larger number of crew members.

The existing sleeping bag system is designed as “one-size-fits-all.” NASA typically designs equipment with sufficient features that it can be used by crew members as small as the 5th percentile Japanese female and as large as the 95th percentile American male, as described by the NASA International Space Station Flight Crew Integration Standard. This presents a challenge in designing the features of the US Sleeping Bag. During development, it was reported in crew evaluations that larger crew members cannot comfortably fit inside the existing sleeping bag because they are too tall. The US Sleeping Bag was lengthened by several inches in order to accommodate taller

crew members. This makes the length of the sleeping bag longer than the internal height of the Crew Quarters. The impact of this discrepancy will be determined by on-orbit use. Another concern with designing for NASA's specified range of crew members is allowing crew members of all sizes to make use of features such as the storage pocket and foot ventilation. To design for this, one common point on the sleeping bag was designated as “common” for all crew members with the remainder of the sleeping bag designed accordingly. The top portion of the sleeping bag contains a hole for crew members inside their sleeping bag to rest the face against (Figure 7). This was designated the focal point for all crew members. From here, sleeping bag features were designed:

- The upper portion of the sleeping bag was lengthened to accommodate longer crew members.
- The arm slits were lengthened and angle adjusted to accommodate the wide range of torso sizes/shapes.
- The storage pocket position was adjusted to accommodate shorter arm lengths, allowing smaller crew members to easily reach into the pocket.
- The foot opening (Figure 8) was repositioned higher in the sleeping bag and geometry changed to allow shorter crew members to stick the feet out for ventilation. The flap covering the foot opening was also reversed in order to more easily facilitate the occupant opening the vent with their feet, negating the need to partially egress the sleeping bag to open the vent.
- A gusset was included to accommodate larger crew members, or those who wish their sleeping bag to be less snug against the body.

Designing for this range of occupants requires some concessions. The higher positioning of the foot opening means that larger crew members who use the feature for feet ventilation will need to protrude both their feet and lower legs out of the opening, potentially inducing more ventilation than desired. Crew members at the



Figure 8. Foot opening (flap fastened open).

dimensional extremes will find their arms protruding through the arm slits at the far ends of slit, which is less comfortable than if they protruded from the center of the slit. During crew evaluations in development of the US Sleeping Bag it was determined that these concessions were acceptable in order to best accommodate the widest range of potential crew members.

D. Additional Functionality

Other minor features were added to enhance the functionality of the US Sleeping Bag and improve the user experience. These were identified during project development in conjunction with the JSC Astronaut Office based on crew experiences with the existing sleeping bag system aboard the ISS. These additions are intended to provide additional versatility and flexibility in the US Sleeping Bag should crew preference desire usage of the features. The features are simple and lightweight, making them useful additions to the sleeping bag.

The storage pocket on the front of the sleeping bag was enlarged to allow the storage of a tablet computer. The pocket closure flap was affixed with a smaller Velcro strip in the center of the flap for easier access to the pocket's contents and faster closure. Snaps are installed on the flap corners for additional security to prevent small items such as medication from escaping the pocket.

Two double zipper pulls were added to the entry zipper. The presence of two zipper pulls allows the occupant to create their own opening in the center of the sleeping bag for ventilation or mobility without completely undoing the restraint that the zipper provides. Making each zipper pull a double pull – one pull inside the sleeping bag, one pull outside the sleeping bag – provides the occupant more options to manipulate the pull from inside the sleeping bag. This system also provides additional safety in case one pull becomes stuck; the other pull can be manipulated to exit the sleeping bag.

Each liner contains an additional flap of material with Velcro attachments behind the head to act as a pillowcase if desired (Figure 9). Some crew members will place soft objects such as folded clothing behind the sleeping bag or head to act as a pillow since the sleeping bag insulation/padding is fairly thin. The addition of the “pillowcase” serves to hold those objects in place so they don't float away and also acts as a hygienic barrier between the occupant's head and “pillow” to keep the objects clean. The “pillowcase” is part of the liner so it is swapped out with the rest of the liner during periodic liner replacement.



Figure 9. Liner flap for “pillowcase.”

The existing sleeping bag design contains two types of ties: cord and ribbon. In evaluations with the crew office it was determined that most crew members used the cord design. The US Sleeping Bag uses the cord design, made from a non-flammable material. The number of cords was increased to eight since the cords are lightweight and crew preference on number of cords to attach their sleeping bag to the wall can vary. The cord lengths were also increased to two feet each in order to provide more flexibility in attachment to a structure.

III. Crew Member Feedback from On-Orbit Use

Feedback regarding the experience using the US Sleeping Bag aboard the ISS was received verbally during crew debriefs which took place after the crew members' return from the ISS. Questions were asked regarding overall use of the US Sleeping Bag, the utility of specific sleeping bag features, and any potential design improvements for future iterations of the sleeping bag or sleeping accommodations. Although this feedback is useful in assessing the US Sleeping Bag design and considering future improvements to the sleeping bag, it is important to note that this feedback represents only a small sample size amongst the entire number of crew members who have lived onboard the ISS and did not use the US Sleeping Bag.

Overall, the response from both crew members regarding the US Sleeping Bag was largely positive. Partway through their respective expeditions both crew members utilized the previous sleeping bag and thus were able to directly contrast the differences. The US Sleeping Bag was considered to be a significant improvement on the previous sleeping bag and both crew members preferred to use the US Sleeping Bag. The most notable improvement was the added length and width which made for a more comfortable and less restrictive sleep. The quality of sleep in

the US Sleeping Bag was noticeably better due in large part to this difference. The crew members had varying comments on individual features of the sleeping bag and their utility, biased by their personal sleep preferences.

A. Materials Selection and Thermal Comfort

Regarding materials selection and temperature, one crew member found the US Sleeping Bag to be a little warmer than the Russian sleeping bag. This crew member tended to run warmer than their crewmates, so this could be an issue if the crew wanted to agree on a certain overall cabin temperature. It was suggested that this was probably affected by the one crew member using a different sleeping bag than the other crew members. If everyone had the same sleeping bag, there would be a common bias towards temperature regulation. The crew member also noted that it was their personal preference that the US Sleeping Bag material should be a little thinner.

B. Vents

Regarding the diamond-shaped vents, one crew member did not feel the need to use the vents and kept them closed. The other crew member used the ventilation flaps a lot. The crew member felt they were nice but that the Velcro attachment points wore out after a while, and thus the flaps tended to open or close unintentionally. The crew member manipulated the vent flaps every day. Besides potentially wearing out, the Velcro may not have been generally strong enough to withstand objects brushing over it.

C. Entry Zipper

Regarding the entry zipper, one crew member noted that the double-sided zipper pull was a nice feature. Sometimes the crew member would open the bottom part of the entry zipper to increase ventilation. This would let air in which specifically helped to cool the feet area of the sleeping bag. The crew member kept the bottom section of the zipper open most of the time, which gave a bit of ventilation whenever the crew member moved inside the sleeping bag.

D. Replaceable Liner

Regarding the replaceable liner and colored toggles, both crew members opted to change the liner a minimal number of times during their respective expeditions. One crew member noted that the colored toggles were useful in replacing the liner, and that the liner replacement task was a little convoluted. It is a chore to replace the liner, so this crew member tried to avoid the task. Although the liner replacement is difficult, the crew member wasn't sure how to improve the design to make it easier in the future, although noted that the colored toggles helped. The other crew member noted that the liner replacement task is very complex and needs a lot of space, typically requiring the task to be performed outside of the Crew Quarters and out in the open cabin. The crew member required almost an entire module to perform the liner replacement to allow the sleeping bag to completely expand so that it was easier to see where the liner attached to the sleeping bag. If the space was available, then the liner replacement was relatively easy but still took at least half an hour. The crew member noted that the difficulty in replacing the US Sleeping Bag liner was comparable to the same task on the Russian sleeping bag. It was stated that the US Sleeping Bag's liner was more complex but had the colored toggles to assist and noted that they were a good design feature. The crew member felt that replacement of the sleeping bag liner isn't required to be done frequently, which is fortuitous since it's not something one wants to do often.

E. Expandable Gusset

Regarding the expandable gusset, both crew members made use of the feature. One crew member noted that the snaps along the perimeter to personalize the room in the sleeping bag were a really good design. The crew member liked that they could adjust where on the sleeping bag they wanted more or less space. For example, the crew member's preference was to have less space around the chest because their preferred sleeping position was with the hands folded across the chest and liked when the sleeping bag compressed the hands a little bit. One issue was that the snaps were easy to overcome. For example, with a little pressure the chest snaps would pop open. It was suggested to use snap buttons with a small locking feature or use a stronger snap. The crew member suggested that snaps are best for uses when an individual needs to quickly open and close something. In the case of a sleeping bag, it was speculated that occupants would find their preferred configuration and then leave the snaps alone.

F. Internal Straps

Regarding the internal straps, neither crew members made use of them. One crew member stated that after their first liner replacement they kept the straps behind them and did not feed them through the liner (required in order to use the straps). The other crew member described them as useless. This crew member cut them out of the sleeping bag. The crew member also noted that in their experience nobody straps themselves in to the sleeping bag – this could be an issue in an emergency because, in their view, the occupant would never be able to get out of the sleeping bag. The crew member didn't believe any other crew member used the straps. However, they are also not particularly in the way since the occupant is not lying against the back of the sleeping bag like one does on a mattress.

G. Sleeping Bag Size

Regarding the overall size of the sleeping bag, both crew members noted this as a key improvement to facilitating better sleep. The previous sleeping bag was too small and tight, restricting movement. One crew member noted that the US Sleeping Bag may have been a little bit too big because it had a tendency to rise around the occupant, but otherwise was not a problem. The other crew member did not see the extended length as an issue. Although the US Sleeping Bag length was extended to be technically taller than the interior of the Crew Quarters, once an occupant was inside the sleeping bag it would essentially bulge up and gave the appearance of not being larger than the Crew Quarters. The important thing for this crew member was being able to find a position where they could perform a full body length stretch without boundaries, including pointing the toes. This was important to the crew member, and they were able to do so with the US Sleeping Bag, which was appreciated.

H. Foot Opening

Regarding the foot opening for ventilation, one crew member did not utilize this feature because they did not feel the need for additional ventilation in the feet area, and kept the flap closed. The other crew member thought the design was great and used it a lot, however noted that it was too big of an opening. The feet area was cooling down too much when the flap was opened all the way. The crew member modified their sleeping bag in an attempt to allow the flap to be opened only partially. They noted that this was not an ideal solution, but they were trying to get some sort of regulation of how much area was open for ventilation instead of the extremes of fully open or fully closed. Their modification to allow regulation of the flap opening had a large effect. Additionally, Velcro around the flap wore out after a few months because the flap was opened and closed frequently.

I. Other Notable Feedback

One crew member noted a significant unintended side effect of the combined design changes to the sleeping bag size, entry zipper, and the addition of the expandable gusset. The crew member typically wanted the feet area to cool down to help facilitate good sleep, however the sleeping bag was inadvertently cooling the chest area. When the crew member's head was inside the sleeping bag, the sleeping bag section around the chin would billow out and create a gap. This action was often caused by the occupant's hands across their chest pushing the sleeping bag away from their body. The top of the entry zipper was designed to be loose to prevent uncomfortable friction with the occupant's neck and chin. Together, air is then easily directed in front of the crew member's face down into the gap in the sleeping bag, thus cooling the occupant's upper body. The crew member addressed this by placing a towel in this gap to prevent air from entering the sleeping bag. The crew member also noted that the most common sleeping position is with the arms together on the chest, not at the sides, so this may occur with other crew members as well. The suggestion was to include in the design a way to close the gap underneath the chin but allow to be ripped open in an emergency.

Neither crew member made use of the liner material intended to act as a pillowcase. One crew member noted that they placed towels to the right and left sides of their heads, stuffed on the sides to prevent head movement and provide a familiar feeling of sleeping in a 1g environment. The crew member did not personally want a towel behind the head as that would push the head uncomfortably forward. However, the feeling of fluffy material on both sides of the head was said to be very comforting.

Both crew members varied in how they tied their sleeping bag to the sleep wall of the Crew Quarters. One crew member declined to use any ties and instead free floated, finding that to be the most comfortable. The other crew member utilized two ties on the attachment points at the hips only. In this way, they were able to bed forward or bring the knees up as desired while still keeping the sleeping bag in one orientation. The crew member also utilized a small bungee for some additional flexibility and elasticity.

J. Final Thoughts

One crew member stated that they did not make any modifications to their sleeping bag and wouldn't suggest anything for improvement. This crew member did not feel the need to make use of a few of the sleeping bag's features so did not have any comment on them. They relayed only positive comments regarding the US Sleeping Bag and much preferred it to the previous sleeping accommodations. They also did not believe that the previous sleeping bag contained any features that they wish were transferred to the US Sleeping Bag. Sleep quality was much improved in the US Sleeping Bag compared to the previous sleeping bag.

The other crew member also stated that there were no features on the previous sleeping bag that they wish had been included in the US Sleeping Bag design. This crew member especially liked the larger volume around the feet since it is easy for the feet area to become hot with no air movement. The larger volume facilitated air circulation and ventilation, especially with the gusset on the bottom of the sleeping bag expanded to the maximum. This crew member believed the US Sleeping Bag to be very well-designed and much better than the previous sleeping bag design. Sleep quality was drastically improved in the US Sleeping Bag, especially with the increase in sleeping bag length. The crew member also appreciated the ability to pull the knees up while inside the sleeping bag. This helped to alleviate potential lower back issues by being able to stretch. In this crew member's opinion, lower back issues in microgravity came from a lack of stretching. The US Sleeping Bag facilitates and allows the occupant to stretch, which can potentially help avoid lower back issues on-orbit.

IV. Forward Work

The feedback from crew experience on-orbit is valuable in updating the design of USOS crew accommodations to further facilitate good sleep. Although no redesign is currently planned, a limited number of US Sleeping Bags were built in the first run. It is possible that the design will be revised prior to construction of additional sleeping bags, taking advantage of lessons learned from on-orbit use of the first generation US Sleeping Bag.

A few aspects of the US Sleeping Bag stand out as potential areas for improvement. Primarily, changing the design underneath the chin to prevent air from inadvertently entering and cooling the upper body should be addressed. The process to replace the liner should also receive some consideration, however it appears that changing the liner as frequently as once per month (as originally assumed) is potentially unnecessary; ease of liner replacement may not be a priority. Regarding the gusset, crew members should be queried on their sleep preferences to confirm that the gusset snaps are not cycled as often as originally expected. If so, stronger snaps or snaps with locking features can be used to better hold the sleeping bag's configuration against movement inside the sleeping bag. The internal straps continue to be considered unnecessary and can be eliminated from the design to save on overall mass. The foot opening design should be revised to allow for partial opening, giving additional versatility to the occupant in the amount of ventilation they receive, and strengthened to prevent accidentally kicking open the flap. These improvements can be incorporated with a low risk to inadvertently reducing sleeping bag versatility.

As new crew members fly aboard the ISS for the first time and utilize the US Sleeping Bag, additional insight will be gained to more fully understand the challenges associated with sleeping in a microgravity environment. For future exploration missions where mass and volume are restricted it may also be advantageous to research and incorporate additional features to assist with longer-term use of the sleeping bag. Such features could include anti-microbial materials sewn into the sleeping accommodations to help maintain cleanliness for longer periods of time. Further research and design work is required to consider design changes associated with the additional requirements a long-term exploration mission will necessitate.

V. Conclusion

The feedback received on crew experience with the US Sleeping Bag emphasizes the importance of versatility in this type of hardware. Individuals have very different sleep preferences and it is important to accommodate as wide a range of crew as possible. However, it should be kept in mind that versatility is more than simply "extra" features. If too much is provided (e.g. too much volume in the sleeping bag that the occupant cannot eliminate) then overall versatility is reduced. Similarly, additional features may cause unforeseen useability issues, such as a gap in the sleeping bag allowing unwanted air to cool the occupant's upper body. Extensive testing can help mitigate these unexpected issues, but sleep in microgravity has different challenges that can be difficult to predict. Discussions with crew members who have spent time in microgravity is the best substitute for a technology demonstration in order to obtain the best data possible to make design decisions. Since sleep is critical for crew member health and performance, especially for longer duration missions, the design of sleeping accommodations will be of the utmost importance when preparing for lengthy exploration missions.

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