

Habitability and Human Factors: Lessons Learned in Long Duration Space Flight

Susan D. Baggerman*
NASA, Houston, Texas, 77058

Cynthia M. Rando†
Muniz Engineering Inc., Houston, Texas, 77058

and

Laura E. Duvall‡
Lockheed Martin, Houston, Texas, 77058

This study documents the investigation of qualitative habitability and human factors feedback provided by scientists, engineers, and crewmembers on “lessons learned” from the ISS Program. A thorough review and understanding of this data is critical in charting NASA’s future path in space exploration. NASA has been involved in ensuring that the needs of crewmembers to live and work safely and effectively in space have been met throughout the ISS Program. Human factors and habitability data has been collected from every U.S. crewmember that has resided on the ISS. The knowledge gained from both the developers and inhabitants of the ISS have provided a significant resource of information for NASA and will be used in future space exploration. The recurring issues have been tracked and documented; the top 5 most critical issues have been identified from this data. The top 5 identified problems were: excessive on-orbit stowage; environment; communication; procedures; and inadequate design of systems and equipment. “Lessons learned” from these issues will be used to aid in future improvements and developments to the space program. Full analysis of the habitability and human factors data has led to the following recommendations. It is critical for human factors to be involved early in the design of space vehicles and hardware. Human factors requirements need to be readdressed and redefined given the knowledge gained during previous ISS and long-duration space flight programs. These requirements must be integrated into vehicle and hardware technical documentation and consistently enforced. Lastly, space vehicles and hardware must be designed with primary focus on the user/operator to successfully complete missions and maintain a safe working environment. Implementation of these “lessons learned” will significantly improve NASA’s likelihood of success in future space endeavors.

I. Introduction

The International Space Station program mission is to safely build, operate, and utilize a continuously inhabited orbital research facility through an international partnership of governments, industries, and academia. The ISS was built to be a human outpost in space bringing nations together for the benefit of life on Earth and beyond. The ISS was created based on the experience gained and “lessons learned” from the Skylab and Mir missions. Beginning

* ISS Flight Crew Integration (FCI) System Manager, Habitability and Human Factors Office, 2101 NASA Parkway Mailcode SF3, Houston, TX 77058

† Human Factors Engineering Specialist, Habitability and Human Factors Office, 2101 NASA Parkway Mailcode SF3, Houston, TX 77058

‡ Human Factors Engineering Specialist, Habitability and Human Factors Office, 2101 NASA Parkway Mailcode SF3, Houston, TX 77058

November 2, 2000, humans have had a permanent presence in space onboard ISS. From the inception of ISS through the conclusion of Expedition 8 in April, 2004, 22 humans have logged a total of 3681 days in long duration space flight, accumulating knowledge and skills that will be critical to allow NASA to move beyond low earth orbit and explore Earth's neighborhood. Long duration space flight, onboard the ISS, as well as in previous missions such as Skylab and Mir, have introduced new challenges in the field of habitability and human factors. One of the biggest challenges is building and maintaining a habitable environment in space.

For a vehicle to be habitable it must provide an adequate living environment for humans where they are given ample space and protection from hazards, and measures have been taken to ensure the overall well being of the inhabitants (physical and mental). The goal of human factors, as a discipline, is to design to accommodate the user and not force the user to fit the design. Human factors experts try to increase performance by reducing errors, increasing productivity, and enhancing safety and comfort when humans have to interact with machine interfaces (Wickens, C. D., & Hollands, J. G., 2000).

NASA human factors experts have worked to ensure that the needs of crewmembers to live and work productively in space have been met throughout the ISS Program. As an ISS System, Flight Crew Integration (FCI) has had a major influence on the design, development, and verification of ISS modules and hardware through defined human factors requirements. FCI has provided functional requirements and conceptual designs for habitability hardware, has provided analysis for lighting conditions, and defined processes and analysis tools for on-orbit stowage and internal volume configuration. Additionally, FCI has managed labeling requirements and processes, for both vehicle systems and payloads. Implementation of human engineering requirements in ISS payloads has also been provided. Analysis of human size and strength capability has been performed to ensure that a wide range of crewmembers will be accommodated by ISS. ISS on-orbit operations have been monitored and evaluated for problem resolution of human factors and habitability concerns. Due to the infancy of long duration space flight and the limited experience available in this area, implementation of human factors principles of design has not always been optimal. It is critical to capture knowledge gained during the ISS lifetime, not only quantitatively, but qualitatively, to improve our capability to accommodate the crew in future space programs.

This paper documents and investigates qualitative feedback collected post-flight from every U.S. crewmember that has resided on the ISS to establish "lessons learned" from the ISS Program. A thorough review and understanding of this qualitative data is critical in charting our future path in space exploration. The focus of this paper is on the human factors and habitability data that has been collected. The knowledge gained in space habitability and human factors through on-orbit crew experiences has provided a significant resource of information. This information has resulted in the identification of five critical human factors and habitability problems and "lessons learned", which will be applied to the remainder of ISS and future space exploration endeavors.

II. Methods

Long duration space flight data collected from U.S. astronauts living on the Russian space station Mir during the ISS Phase I Program was used in conjunction with the data collected from crewmembers living on the International Space Station (ISS). Mir data was used to give a more historical view of the current situation on the ISS. Data from the ISS has been collected from each U.S. astronaut after each Expedition since its inception in 1999. In addition, data has also been collected from some Russian cosmonauts that lived on ISS. The data collection is ongoing and to date encompasses a total of 8 Expeditions and 24 crewmembers, not including the taxi/shuttle crewmembers over the last 5 years. The data also includes the construction period of ISS. Various avenues have been used to collect this data, including: crew debriefs, questionnaires, coordination with the Mission Evaluation Room (MER), crew evaluations, and interdisciplinary cooperation.

Crew debriefs are a consistent part of each mission. For crews returning to Earth in a Russian Soyuz vehicle, a series of joint debriefs, meaning both the U.S. and Russian crewmember are present, are held in Russia prior to the debriefs conducted in the U.S. When a joint debrief is provided on the U.S. side, time with both crewmembers is extremely limited and not all topic areas are typically addressed. However, a series of post-flight debriefs with the U.S. crewmember only are scheduled on the U.S. side, providing an opportunity for various NASA discipline groups to follow-up on on-orbit issues and previous debrief comments, as well as collect more detailed data in their subject area..

Questionnaires are developed periodically to address specific concerns that arise, typically from issues identified on-orbit or new hardware development. Questionnaires are distributed to both experienced and novice crewmembers, and cover topics such as hygiene preferences and sleep accommodations. These questionnaires are used to elicit knowledge from crewmembers on their operational experience on-orbit, personal preferences, and suggested improvements, specifically on habitability issues and hardware. Questions may address issues such as:

Do you feel that hygiene and privacy methods/products need to be improved if the duration of a mission extends to longer than 6 months? As the ISS crew size increases and mission durations potentially get longer, the data gathered from such questionnaires will be used to engineer a more habitable living and working environment.

Mission Evaluation Room (MER) provides on-console engineering support for problem resolution for the on-orbit issues that the crew may have with systems or hardware. This resource will work real-time issues that may arise day-to-day on ISS, providing interim and long-term resolution of problems. For example, human factors is consulted when there are labeling issues with hardware or emergency equipment. Human factors personnel participate as members of the MER team; this has been an invaluable way to obtain data and remedy problems real-time.

Crew evaluations are a designated block of time set aside for the crew on the ground to evaluate hardware that is to be manifested on a future flight. During this time the crew and human factors experts can evaluate features of the hardware for its usability, maintainability, and its effects on habitability onboard the ISS. Crew evaluations are typically conducted with crewmembers ranging in experience (short duration, long duration, and no spaceflight experience), gender, and size (small female to large male). Feedback from crewmember participants is documented through the use of quantitative and qualitative questionnaires, photographs, audio/video recordings, and notes from the evaluation conductor.

Interdisciplinary cooperation provides for engagement of human factors experts early in the design process to ensure the best human interface design possible. Experience has shown that incorporation of human factors and habitability requirements and design principles early in the development process positively affects the design of a piece of hardware/software and limits the operational/re-engineering cost to the Program associated with a poor design. The human factors team primarily interfaces with hardware developers, safety personnel, ISS Program management, mission operations personnel, and the crew office.

Information gathered through all of the defined methods has been analyzed and evaluated for habitability and human factors issues and “lessons learned” to be applied to the future of ISS and to upcoming human spaceflight programs.

III. Results/Discussion

Crew comments and “lessons learned” have been captured and tracked in a database for the Mir and ISS programs by the habitability and human factors team. Each comment entered into these databases has been subjectively evaluated and dispositioned as positive, negative, or neutral in nature. The negative comments have been considered the most useful in determining “lessons learned” for future flight programs. Positive and neutral comments were also considered to be valuable sources of data to confirm success in the Mir and ISS Programs. 934 comments pertaining to the Mir program have been logged, 46.8 % of which were negative in nature. To date, 1519 comments have been logged pertaining to the ISS program, 51.3% of which were negative in nature. The recurrence and relative significance of these documented comments have been tracked and the most critical “lessons learned” to be used in future exploration have been defined.

A. Excessive On-orbit Stowage

Historically, excessive stowage has been a primary concern for the ISS based on the events and experiences on Skylab and Mir. Human engineering experts predicted that stowage would be a problem for ISS if avenues were not taken to augment the amount of living and storage space available to the crew on the ISS (Blume-Novak, J., 2000). Stowage comprised 13.1% of all total comments for Mir, and 68.0% of the stowage comments were negative in nature (see Table 1). Crew comments and “lessons learned” have shown NASA that excessive stowage is once again an issue for another long duration flight program. ISS stowage comprised 11.5% of all total ISS comments (to date), and 46% of the stowage comments were negative in nature (see Table 1). The excessive ISS stowage has been a crew issue since Expedition 1 and has continued to be cited as a crew concern throughout all eight of the eight Expeditions to date. As identified by the crew during post-flight debriefs, stowage has been a top habitability concern for four out of the eight Expeditions (see Table 2).

There are multiple reasons for why stowage has become a top priority to rectify. These reasons include:

Imbalance of manifest and down mass

It is critical to balance the launching of supplies (manifest) with the ability to dispose of waste and return items to Earth (down mass) in order to maintain habitable conditions on ISS. The stowage situation onboard ISS has recently worsened, because of an imbalance of manifest and down mass, due to the grounding of the Shuttle after the

Columbia accident. Over a period of time, the on-board inventory of supplies in certain areas (clothing, hygiene, etc) accumulated while manifesting of these supplies continued. Each Expedition crewmember would bring a selection of personal items with them to the ISS and at the end of their stay, the unused items would remain. This situation improved as the inventory management function improved and the manifesting process was streamlined, but continued to be a problem due to the lack of disposal capability through Shuttle flights.

Inadequate stowage tracking system/methodology

The tracking methodology for items stowed on ISS has not been consistent with every Expedition. Items were not stowed adjacent to each other based on their functional use, causing crewmembers to have to search at opposite ends of the station for items needed for one particular activity. The inventory management system (IMS) on ISS was not used consistently to track items to be stowed, and not all items were tracked. When items were moved they were not always placed back in their designated area and IMS was not always updated to reflect their new location. As NASA's experience on ISS has increased, this issue has improved. Items are now more consistently labeled with IMS barcode labels, and the tracking system is significantly more accurate.

Stowage management and inadequate stowage volume

ISS is only six years old and it is already exceeding its stowage volume capabilities. Currently on-board waste accumulation is exacerbated by the buildup of packing materials that arrive with each shipment. Limitations associated with the ability to dispose of packing materials results in excessive amounts of stowage space utilized for waste. The amount of stowage on board has increased to the point where all designated stowage areas are full and items are now being stowed in areas intended for habitability and work related functions. Items are now stowed in passageways and in front of other stowage areas. When searching for items it is necessary to move many other stowed items out of the way to gain access to the panels where a desired item is located. During a previous Expedition, stowage located in the aisle way was blocking emergency fire ports. Although this specific issue has been resolved on-orbit, it serves as an example of the risk excessive stowage can impose on the crew's safety.

Overall Recommendations

To remedy the stowage situation on ISS and prevent this issue from occurring on future Exploration programs, several steps need to be taken: 1) All disciplines need to coordinate the amount and type of items manifested and disposed of with one central group, which is a current focus in the ISS Program. NASA is working to better monitor and plan what type and how many items are manifested and the disposal of those items. A stowage system needs to be strategically planned for future exploration, where manifesting and disposing of items may become more difficult. 2) With the introduction of new technologies, future exploration programs should utilize new methods to more efficiently track items and minimize crew time required for inventory tracking. It is also important to ensure that all hardware is fully identifiable and able to be easily tracked. 3) The program needs to evaluate how to better pack items for launch, specifically, how much and what types of packing materials are used. Packing materials currently used must be disposed of, thereby creating additional waste burden for the crew and vehicle. Manifesting of flight items is a critical priority requiring very comprehensive planning and warrants heavy monitoring to avoid making the mistake of exceeding stowage volume available on future exploration missions. The data collected from both Mir and ISS should be assessed to evaluate the stowage volume needed for a future long duration flight and account for that volume as a critical requirement and design driver for a future vehicle. Stowage should be treated as its own system and the volume allocated for stowage should have the same priority as volume required for other systems.

B. Architecture and Environment

Concerns relating to the state of the environment, as defined as the crew's surroundings, in long duration space vehicles have been present since the Mir program. Environmental comments comprised 36.1% of all comments for Mir, 47.2 % of which were negative in nature (see Table 1). Crew comments and "lessons learned" have shown NASA that the environment continues to be an issue for ISS. Environmental comments comprised 15.3% of all total ISS comments (to date), 55.6% of which were negative in nature (see Table 1). The environment in which the crew works and lives has been a primary issue since Expedition 1 and has continued to be an issue throughout eight of the eight Expeditions to date. As indicated by the crew, the environment has been a top habitability concern for three out of the eight Expeditions (see Table 2).

There are several reasons for why the environment on the ISS has become a top priority to rectify. These include:

Poor lighting design

The lights, particularly in the Node 1 module, were not installed to afford the maximum amount of light output provided by the design of the lighting fixture. The lights also began to fail in all areas during the last three Expeditions, and this is only one-third of the way into the station's total life expectancy. Replacement lights are currently being manifested on Russian Progress vehicles, but this mass and volume allocation is at the expense of other U.S. items that need to be delivered to Station. The Node lighting has been further impacted by the excessive stowage that blocks existing light and the lack of reflectivity of surrounding surfaces. Panels were designed without adequate lighting behind them, consequently forcing the user (crewmember) to accommodate for the poor design by using other types of portable lighting while searching for items behind the panels.

Co-location of dining area, exercise equipment, crew quarters, and waste collection system

The crew dining area, two of the three crew quarters, the Russian cycle ergometer, treadmill, and the waste collection system are all located in the Russian Service Module. The co-location of all these items leaves limited volume for translation and does not allow for multiple crewmembers to exercise and dine at the same time. For hygiene reasons, a crewmember will not exercise while another crewmember is eating because of sweat droplets that tend to float through the module during exercise. When the ISS has visiting crewmembers this problem becomes exacerbated and necessitates eating and exercising in shifts since the dining table only accommodates three crewmembers and all crewmembers are required to exercise daily. This fragmentation of crew activities, especially dining, does not promote crew unity.

Excessive noise levels

The ISS houses the crew, functions as their workshop and laboratory, and is where they spend all of their leisure time. The acoustic situation is complex with many different types of noise generating hardware. The cumulative noise manifests itself in two forms: continuous and intermittent. The continuous noise results from the operation of pumps, fans, compressors, avionics and other noise producing hardware or systems, while the intermittent noise is caused by hardware that operates cyclically, such as exercise equipment or the carbon dioxide removal system. Over the span of all the crew noise exposure measurements, approximately two-thirds of these do exceed the flight rule requiring the use of hearing protection for levels of 67 dBA or higher over a continuous twenty-four hour period. Most crewmembers choose to wear earplugs or noise-canceling headsets to mitigate the continual noise. However, the prolonged use of earplugs and headsets could have health implications. Some crewmembers do not adapt well to the constant irritation of earplugs in their ear canals or the pressure of the headsets. When communicating with the ground, the crew must raise the volume to overcome the background noise. Elevated noise levels can also prevent the crew from hearing monitor signals and warning alarms. The crew's ability to communicate with each other is impaired; verbal communications with each other only works when both crewmembers are in the same module within a few feet of each other, and this is not an optimal way for the crew to communicate (National Aeronautics and Space Administration Johnson Space Center, 2003).

Overall Recommendations

To improve the state of the environment several steps can be taken: 1) Lights should be designed to meet the needs of the mission. Lighting should be installed for maximum output, designed for longevity, reflectivity of surfaces, and orientation of workstations. In addition, storage compartment lighting should be considered to facilitate ease of managing stowed items. 2) Vehicle topology, specifically, layout of crew habitability functions, is critical in the usability and operability of the vehicle. Public areas, such as the galley and food consumption area, should be co-located, but located away from the private areas; such as the crew quarters. Additionally, areas related to hygiene, such as the waste collection system and exercise hardware should be located away from eating areas. 3) Acoustic abatement strategies and methods should be incorporated early in the design of a vehicle. These should include the thoughtful design of functional layout of the vehicle (if possible, isolate the noisy mechanical operations from the crew habitation area) and ensuring that hardware from all providers meets acoustic requirements. Inherently noisy hardware, such as exercise equipment, should use noise control engineering strategies to reduce acoustic emissions.

C. Communication

Communication was also repeatedly documented as an issue during the Mir program. Communication comments comprised 6.5% of all total comments for Mir, 60.7% of which were negative in nature (see Table 1). Crew comments and "lessons learned" have shown NASA that inadequate communication methods continue to be an issue

for ISS. Communication-related comments comprised 6% of all total ISS comments (to date), 61.5% of which were negative in nature (see Table 1). Crew communication has been a leading issue since Expedition 1 and has continued to be cited as a crew concern throughout all eight of the eight Expeditions to date. As indicated by the crew, communication has been a top habitability concern for two out of the eight missions (see Table 2).

There are multiple reasons for why communication has become a top priority to rectify. These reasons include:

Language Barriers

With multiple nationalities co-existing on ISS, accurate translation of one language to another can be difficult and cause problems. One particular problem for the crew has been the extensive use of acronyms and abbreviations on board ISS. The acronyms and abbreviations are not universal and have caused the crew extra time in determining what a label means and identifying the hardware. For one Expedition, use of the Russian keyboard for Russian items was particularly challenging, because of limited experience with this type of interface. Another documented issue was that the inventory management system required rebooting to switch languages. In addition, words can be misinterpreted between crewmembers and cause conflict between the crew or partner countries.

Limited communication capabilities

The ability to hear voice communication with the ground is sometimes degraded, costing the crew extra time to clarify issues and repeat things to the ground. There is no wireless communication system available to the crew to facilitate communication across the modules, which is extremely difficult due to noise levels. The current system consists of audio terminal units (ATUs) located at the end of the modules, which the crew must translate to in order to talk to the ground or between ISS modules. An estimated 6 hours/week of crew time is spent translating to an ATU for communication. During drills and caution and warning alarms the crew has had difficulty in contacting the ground with out acknowledging the alarms first, which can take up to 20-30 minutes.

Miscommunication between the ground and crew

During the earlier missions there were several communication frustrations between the crew and ground. Many of these issues were caused by the lack of effective verbal communication between crew and ground about the reality of on-orbit life. Ground operators had difficulty understanding how much time it really took to complete tasks on orbit in microgravity, and this would cause stress and discord between the crew and ground. Many times the crew has not been aware of what the ground can assist with and there are many things that can be automated to facilitate crew productivity. However, in recent Expeditions the ground has been working hard with each of the crews to better assess constraints and limitations of on board life.

Overall Recommendations

To improve the communication capabilities several steps can be taken: 1) Continue the comprehensive cross-cultural training programs, extensive language training, and time spent in partner countries. Better enforce hardware labeling requirements and eliminate the use of acronyms and abbreviations on hardware and in procedures. 2) When designing future space vehicles, include a wireless system for both intra-vehicle (crew-to-crew) communication and crew-to-ground communication. Consider installing a wireless communication system on ISS to augment the current ATU-based system. 3) Continue to encourage open communication between the crew and ground controllers, and provide real-time problem solving to the crew. Provide feedback data to ground controllers, hardware developers, and procedure writers on the amount of time that tasks take to complete on-board for their use in future development. Investigate on-board activities that could be automated from the ground, saving crew time on-orbit. Provide flexibility in scheduling by allowing the crewmembers to allocate their own time whenever possible.

D. Procedures

Procedures were not a top habitability issue for the Mir program; of 934 comments recorded, only 5 comments were related to procedures. Procedural related comments comprised 0.54% of all total comments for Mir, 60.0% of which were negative in nature (see Table 1). Crew comments and “lessons learned” have shown NASA that inadequate procedures were not a big concern for the Mir program, but have become an issue for ISS. Procedural related comments comprised 7.6% of all total ISS comments (to date), 58.3% of which were negative in nature (see Table 1). Procedures have been a commonly cited issue since Expedition 1 and have continued to be highlighted as an issue for eight out of eight Expeditions. As indicated by the crew, procedures have been a top habitability concern for one out of eight Expeditions (see Table 2). There are a variety of reasons for why procedures have become a top priority to correct. These include:

Procedures are too complex

The crew has consistently referred to procedures as too lengthy and difficult to follow, which has caused the crew to be unable to complete scheduled activities within the allotted time. The procedures have lacked the simplicity necessary to complete tasks efficiently in space. Accordingly, the procedures need more diagrams and photos to increase their usability. In some cases procedures have referenced multiple steps in several different procedures, costing the crew additional time in locating the necessary steps and difficulty in following procedures.

Electronic procedures were not always useful

The crew has faced some difficulties with easily using electronic procedures. Frequently, the crew had to spend a lot of time navigating between various menus because the procedures were so difficult and too lengthy. Many of the electronic updates were to be printed out to update procedural books, costing the crew time with printing and changing out procedure pages. Printing has been notoriously difficult on orbit; therefore, it is not optimal to send up long electronic procedures.

Overall Recommendations

To improve procedures, several steps can be taken: 1) Evaluate all current and future procedures for their usability and executability. Simplify procedures by using more graphics, fewer words, and more intuitive, less complex wording. Develop procedures to accommodate expert vs. novice users, and users from multi-cultural backgrounds. Experts with a system will require a lower level of detail with the procedures they are using than a novice. When experts become familiar with procedures it is possible that they may skip a crucial step due to too much familiarity and confidence with the system. It is necessary to circumvent this error by providing a shorter procedure for the expert and a longer version for the novice. This will help the expert user avoid skipping important steps in the procedures and will help make sure the novice has enough detail provided. 2) Evaluate all procedures to be sent electronically for length and usability. Decrease the need for the users to have to scroll through procedures or use multiple screens to view the procedures. If there are major updates to certain paper-based procedures, consider manifesting a new procedure book.

E. Lack of Human Centered Design

Success of a design should be measured when two goals have been reached 1) the item functions as intended, and 2) people can use it. Human centered design attempts to accomplish these goals of functionality and usability by designing to accommodate the user within the design. While accessibility, maintainability, and labeling are three aspects of human-centered design that have been often cited by the crew, there are many other aspects of this concept that need to be considered for a future human spaceflight program. The full scope of human centered design involves designing complex systems to support human capabilities and limitations to meet mission goals and task objectives. Defining the process of human-centered design to enable design engineers to implement its practices and principles will be of paramount importance for the success of future human exploration of space.

The usability of the design of systems and equipment on the space station Mir raised moderate levels of concern amongst the crew. Design related comments comprised 11.2% of all total comments for Mir, 40.0% of which were negative in nature. Crew comments and lessons learned have shown NASA that inadequate space design methodologies continue to be an issue for ISS. Design related comments comprised 26.3% of all total ISS comments (to date), 60.4% of which were negative in nature (see Table 1). The inadequate design of systems and equipment has been a leading issue since Expedition 1 and has continued to be headlined as an issue for seven out of eight Expeditions. As indicated by the crew, inadequate design of systems and equipment has been a top habitability concern for two out of eight Expeditions (see Table 2).

There have been a variety of reasons associated with why the design of systems and equipment has been identified as a top issue. These include:

Accessibility

Due to the overall design of the U.S. modules, accessibility has been a constant problem for the crew. These modules were designed to require numerous tools to access areas within the module; specifically, most panels are attached with fasteners that require tools to disengage. In space, this type of design has proven ineffective; the crew has had trouble accessing items in a timely manner because panels often contain an excessive number of fasteners (as many as 12 – 14 per panel) and the operation of the fasteners is not always intuitive. Not only has this cost crew time, it has been a source of frustration for the crew. With the mounting stowage problems, there is a need to stow

items in front of panels and in translation paths decreasing the crew's ability to access items quickly. Cable routing also blocks access to panels and stowage locations. In addition to accessibility problems caused by obstructions, the crew has also experienced problems due to the design and integration of hardware. The U.S. segment of the ISS is composed of "racks" that were designed to rotate to provide crew access to the rack utility connections and the module wall. However, crew feedback has indicated that rotating racks is not an effective way to access utilities and connectors in a microgravity environment. The clearance required for human accessibility was repeatedly cited as an issue. The design of panels and drawers has also compromised crew accessibility because many of them "stick" on-orbit. Finally, overall topology negatively affected crew accessibility. As an example, the U.S. cycle ergometer blocks access to the Lab window. Physical and visual access to on-board windows is very important to the crew for their habitability and mental health.

Maintainability

Maintainability of systems on a long-duration orbiting vehicle such as ISS is critical. Currently, most hardware, particularly on the U.S. segment, requires many tools to be maintained. While the ISS tool kit has improved greatly since the early ISS Expeditions, the quantity of tools required for maintenance is excessive for a microgravity environment. Additionally, many hardware items require frequent maintenance. This is a significant impact to crew time, particularly when the need for frequent maintenance is coupled with the limited accessibility of items on-orbit. Design of utility equipment, such as connectors and latches, has not been standardized on ISS, which can cause crew confusion when operating hardware. Equipment intended to be moved around on-orbit needs to be designed with ease of relocation in mind. As an example, the handrails on ISS were designed to be moveable but early ISS crews found their attachment mechanism somewhat difficult to use.

Inconsistent labeling practices

Labeling has been a significant issue for the crew for many reasons. One reason has been that NASA has extensively used acronyms throughout the ISS Program. The use of acronyms has become a problem because they are not intuitive to the crew, there has been overuse of acronyms, and some acronyms have been used to refer to more than one type of item. Not only has the use of acronyms overextended its usefulness on orbit for the U.S., but it also causes problems for crewmembers of other native languages and cultures. Another issue is inconsistency in labeling; many items have been flown without labels or with insufficient information provided on the label. Some hardware is labeled with the part number only and does not contain an operationally relevant name or inventory management system (IMS) barcode. This causes confusion for the crew in identifying the hardware. Missing labels have been identified as a problem, particularly for cables and hoses, resulting in the crew incorrectly installing items. Inconsistency has also occurred among modules in location coding schemes. Lack of operational instructions on hardware, such as fire extinguishers and orbital replacement units (ORUs), has also been identified by the crew as an issue.

Overall Recommendations

To improve the overall habitability of ISS the following steps can be taken: 1) Implement early and continued involvement of human factors during the conceptual design stages and ensure that human factors personnel are an integral part of every design team. Design future space vehicles with human accessibility as a central design driver. Allow access to panels and hardware through the use of manually activated fasteners, requiring no use of tools. Provide sufficient designated areas for items that can obstruct physical access, such as stowage and cable routing. Evaluate accessibility needs to ensure that sufficient volume is provided for a full range of crewmembers. Design the topology of a vehicle with the user as the central focus; define and protect for operational volumes for access and use of all equipment. 2) Hardware and systems should be designed with durability/reliability and maintainability as primary drivers. Frequency of required maintenance, as well as tools required for maintenance, should be minimized. Design of common equipment, such as connectors and latches, should be standardized throughout a vehicle. 3) Clearly define labeling requirements and processes at the beginning of a new program to ensure consistency. Provide information on labels that is useful to the crew, and that can be used in inventory tracking. Provide operational labeling (instructions) directly on hardware when feasible.

IV. Summary

Collectively, excessive stowage, environmental factors, impediments to clear communication, unclear and lengthy procedures, and the inadequate design of systems and equipment have all contributed to a degraded habitable living and working atmosphere on board the ISS. Because each of these issues has had a recurrent

presence as documented issues over the past five years, they have been identified as the top five critical lessons to be learned from this Program. Given a full analysis of the on-orbit data collected pertaining to habitability and human factors to date, the following conclusions can be made. It is of paramount importance for human factors to be involved early in the design of space vehicles and hardware. Human factors requirements need to be readdressed and redefined given the knowledge gained during ISS and previous long-duration space flight programs. Upon their update, these requirements must be integrated into vehicle and hardware technical documentation. Lastly, design of space vehicles and hardware must start with the user or operator, and be designed to fit their needs. The operational concept for the use of a vehicle or hardware must be designed and understood before the design process begins. Implementation of these “lessons learned” will significantly improve the likelihood of success of a future human exploration mission. Providing a healthy environment for crew productivity in working and living in space is a critical piece of the puzzle for extending our human presence beyond low earth orbit.

Appendix

	Total number of Mir specific issue comments	% of Mir comments that were negative	Total number of ISS	% of ISS comments that were negative
Excessive On-orbit Stowage	122	68.0%	174	46.0%
Architecture & Environment	337	47.2%	232	55.6%
Communication	61	60.7%	91	61.5%
Procedures	5	60.0%	115	58.3%
Lack of Human-Centered Design	105	40.0%	399	60.4%

Table 1: Total number of habitability issue comments and percentages of those comments that are negative in nature

	Expedition							
	1	2	3	4	5	6	7	8
Excessive On-orbit Stowage	★			★	★			★
Architecture and Environment	★			★				★
Communication		★				★		
Procedures							★	
Lack of Human-Centered Design			★	★				

Table 2: Identified habitability issues by Expedition (shaded in areas indicate a category was identified as a habitability issue for that Expedition.



-Star indicates a category was identified by the crew as a TOP habitability issue for that Expedition

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