Risk of Reduced Safety and Efficiency Due to Inadequately Designed Vehicle, Environment, Tools, or Equipment

Susan Schuh
Wyle Integrated Science and Engineering Group

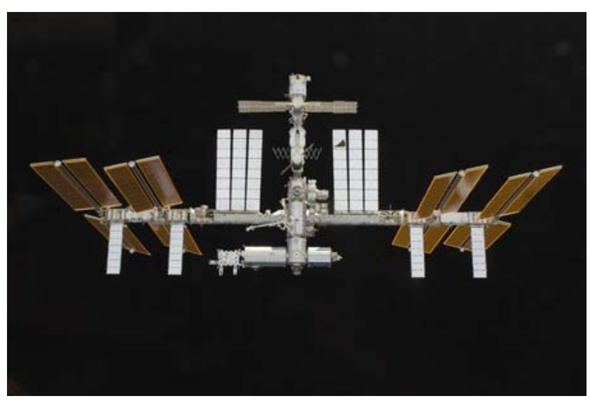
Abbe Barr
Lockheed Martin Corporation

Janis H. Connolly
NASA Johnson Space Center

Barbara Woolford
NASA Johnson Space Center

Mary Kaiser
NASA Ames Research Center

The habitability of the architecture, habitable environment, tools, and equipment is critical for the existence of humans in space. Any inadequacies in the design of the environment or architecture can restrict or prevent the user from surviving in such extreme conditions and may impact safety and performance. Factors that affect the habitability must be assessed and properly addressed to ensure all potential hazards are mitigated or monitored. If the workspace, equipment and tools are not designed to be usable by the full range of crew members, and are not properly laid out, the likelihood of errors or crew inability to complete a task in a timely manner increases. Inconsistent design among subsystems and vehicles leads to negative transfer of training and increased likelihood of errors. – *Human Research Program Requirements Document*, HRP-47052, Rev. C, dated Jan 2009.



The ISS (photographed by the departing STS-127 astronauts as they begin their return to Earth) is a highly visible example of a successful cooperative endeavor. Integrating human factors principles into environmental and architectural designs for hardware, software, vehicles, and habitats is required to ensure the usability of space systems and the safety of space travelers.

Executive Summary

The primary goal of the SHFH Element for human space exploration is to preserve the safety of the crew, promote human performance, and increase efficiency while on orbit. This goal is achieved by integrating human factors principles into the environmental and architectural design for hardware, software, vehicles, and habitats. In particular, optimal on-orbit environmental conditions and architectural design are critical for the health and well-being of space flight crew members as well as the habitability of vehicles and habitats. Optimized usability in the design of workspaces, equipment, and tools for the remote space flight environment is also important. Evidence that is captured in this chapter emphasizes the importance of human factors design considerations, and also illustrates how operator safety and efficiency can be jeopardized when these considerations are not addressed throughout the system life-cycle process for vehicles, environments, tools, and equipment. For a more detailed summary of overall concepts that are related to space flight human factors and human-centered design, refer to Chapter 9 of this document.

Introduction

The purpose of the space human factors discipline is to create and maintain a safe and productive environment for humans in space, which requires an understanding of human performance and limitations. Inadequate implementation of human factors design in work environments will result in reduced human performance, an increased likelihood of human errors, and decreased mission safety and effective mission execution. These potential, negative outcomes emphasize the need for focused, human-centered design that will assist in the development of hardware, software, and tools that are better designed to fit the human and reduce overall human safety risks to the program. With missions using new technologies at an ever-increasing rate, it is imperative that these advances enhance crew performance without increasing crew workload, stress, or risk. It is important to identify concerns that require a space human factors assessment and highlight the value of space human factors and safety on orbit.

This chapter focuses on evidence that is related to the risk of reduced safety and efficiency due to inadequately designed vehicles, environments, tools, and equipment. This evidence emphasizes the importance of human factors design considerations, and illustrates how operator safety and efficiency can be jeopardized when these considerations are not addressed throughout the life cycle of vehicles, environments, tools, and equipment.

Evidence

Evidence that is presented in this chapter encompasses lessons learned from 50 years of space flight experience that is related to the risk of reduced safety and efficiency due to inadequately designed vehicles, environments, tools, or equipment. As with the rest of this book, evidence is classified by categories. Category I and Category II evidence consists of quantitative and qualitative findings from research and development. Data are classified as Category I or Category II, depending on the specific testing protocol that was used and the data that were sought. Category III evidence consists of summaries of subjective experience data, as well as non-experimental observations and comparative, correlation, case, and case-series studies. It should be noted that some evidence, which is essentially Category III evidence, is derived from the ISS Life Sciences Crew Comments Database. Although summaries of ISS crew comments are presented as evidence here, the Life Sciences Crew Comments Database is protected and, therefore, is not publicly available due to the sensitive nature of the raw crew data that it contains.

Category IV[17] evidence consists of expert committee reports and respected authorities' opinions that are based on clinical experiences, bench research, and "first principles."

Evidence that is described in this chapter details human space flight safety and human performance efficiency issues that are related to environmental and architectural design as well as to the usability and design of workspaces, equipment, and tools. When these aspects of design are inadequate, overall habitability is affected; these issues must therefore be assessed and properly addressed to ensure that all potential hazards are mitigated or monitored. If the workspace, equipment, and tools are not designed to be usable by the full range of crew members and are not properly laid out, the likelihood of errors or of the inability of the crew to complete a task in a timely manner increases. Inconsistent design of subsystems and vehicles leads to negative transfer of training and an increased likelihood of errors.

Environmental and architectural design

Optimal on-orbit environmental conditions and architectural design are critical for the health and well-being of space flight crew members and the habitability of vehicles and habitats. Any inadequacies in the design of the architecture or the environment that is built can affect the safety and performance of the human. The environmental and architectural factors affecting habitability must be assessed and properly addressed to ensure that all potential hazards are mitigated or, at a minimum, monitored. Noise and lighting issues are specific environmental issues that are experienced on orbit that affect habitability. Issues that are related to environment depend on the manner and extent of exposure to environmental elements. Architecture issues that impact habitability are related to the design, configuration, and topology of the interior volume of space vehicles and modules and to the co-location of systems and tasks. They include issues that are related to human translation (movement from one location to another) and orientation information as well as problems that have occurred when vehicles, habitats, or other hardware designs did not accommodate the user.

For example, noise is a pervasive aspect of all living and working environments that can, at times, present hazards. The ISS acoustic environment, in particular, is complex, and includes many types of noise-generating hardware because the ISS provides not only home for the space flight crew, but also their workshop and laboratory (Rando et al., 2005). The cumulative effects of the ISS acoustic environment manifest themselves in two forms: continuous and intermittent noise (Baggerman et al., 2004). Continuous noise is generated by the operation of pumps, fans, compressors, avionics, and other noise-producing hardware or systems. Intermittent noise is caused by hardware that operates cyclically, e.g., exercise equipment or the carbon dioxide removal system. On-board acoustics measurements in various ISS modules often exceed the ISS flight rules for noise exposure and can be at 67 dB or higher over a cumulative 24-hour period (Goodman, 2000; Clark and Allen, 2008). Issues and constraints that are related to the acoustics environment increase the risk of impacts on crew safety as the crew may not be able to hear the C&Ws. Although C&W tones are typically audible, noise within the ISS from daily operations and activities has sometimes impeded the crew's ability to hear the C&W tones.

---

[17]To help characterize the kind of evidence that is provided in each of the risk reports in this book, the authors were encouraged to label the evidence that they provided according to the "NASA Categories of Evidence."

- Category I data are based on at least one randomized controlled trial.
- Category II data are based on at least one controlled study without randomization, including cohort, case-controlled or subject operating as own control.
- Category III data are non-experimental observations or comparative, correlation and case, or case-series studies.
- Category IV data are expert committee reports or opinions of respected authorities that are based on clinical experiences, bench research, or "first principles."

This inability to hear can also affect efficient mission performance by interfering with communication between crew members as well as between the crew and the ground. As documented in the ISS Life Sciences Crew Comments Database, noise has interfered with communication between crew members in different modules as well as between crew members in the same module. Noise has cost crew members time as they translate between modules to communicate directly. Wearing hearing protection because of high noise levels also impacts communication (figure 10-1). In addition, some crew members have reported that excessive noise on station has negatively contributed to their perception of ISS habitability. For instance, on-board noise has wakened some sleeping crew members. These examples show the need for optimal environmental conditions, such as acoustic levels that are below unacceptable noise thresholds, and the appropriate provision of auditory information (Category III).

Figure 10-1. ***ISS018-E-027439 — Cosmonaut Yury Lonchakov, Expedition 18 flight engineer, wears a hearing-protection device as he uses an oscilloscope to measure voltage in the Pirs docking compartment of the ISS (NASA Human Spaceflight Gallery, 2008)*****.**

The provision of adequate lighting conditions is also essential for any living and working environment, including on board ISS. Although the station has increased substantially in size, it still remains a confined environment in which crew members live and work. It limits them to only the lights that are provided in modules and the additional lighting that is provided by portable and handheld lights. The evidence that is described below emphasizes the importance of providing appropriate lighting conditions.

Several issues have arisen with lighting on board the ISS (Baggerman et al., 2004). Lighting in some of the ISS modules was not originally installed in a manner that would provide the maximum amount of light output that had been designed into the lighting fixture. In addition, lights have failed throughout the life of the ISS, and limits on shuttle and Soyuz launch mass and volume have prevented the delivery of replacement light fixtures. Lighting in the ISS Node 1 module has been further affected by excessive stowage that has blocked operational lights, thus reducing the reflectivity of the surrounding surfaces. Because of the low lighting levels, some crew members have had to move certain tasks out of Node 1 to perform them, which both increases the time that is necessary to perform tasks and decreases efficiency. Working behind panels or racks without dedicated lighting has been difficult for some of the crew members. This situation forces them to accommodate and make up for the poor design by using other types of portable lighting while they are searching for items or working behind panels. In summary, these impedances and inadequacies related to the ISS lighting have contributed to risks to efficiency on board the station (Category III).

Inefficiencies in space flight vehicle and habitat architectural design as well as the co-location of systems and tasks can affect crew safety, efficiency, and habitability. The co-location of certain functional habitability areas has been problematic throughout long-duration space flight due to vehicle size and topology constraints (figure 10-2). Lessons-learned summaries from the data that were collected in the ISS Life Sciences Crew Comments Database provide evidence that, on board the ISS, the adjacency of sleeping quarters with waste and hygiene facilities has not proven optimal due to the noise that is made by the equipment, which disrupts crew sleep. The co-location of the dining facilities near the exercise equipment and waste collection facilities compromises meal scheduling by influencing when food preparation and dining can be done. Although it is still possible to conduct dining activities while other crew members are exercising or using the Waste Collection System, it is not optimal. In addition, locating the dining facilities near the laboratory work jeopardizes both the habitability of the station and the integrity of its science activities. The integrity of science can be compromised by the introduction of foreign debris (e.g., food products), which can alter the results of an experiment by contaminating an environment that should be controlled.

Figure 10-2a. ***ISS008-E-21921 — Astronaut C. Michael Foale, Expedition 8 commander and NASA ISS science officer, equipped with a bungee harness, performs squat exercises on the Treadmill Vibration Isolation System in the Zvezda service module (NASA Human Spaceflight Gallery, 2008).***

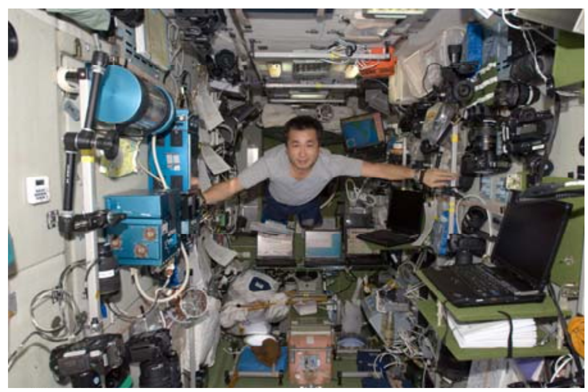


Figure 10-2b. ISS019-E-010232 — ***Japan Aerospace Exploration Agency astronaut Koichi Wakata, Expedition 19/20 flight engineer, floats in the Zvezda service module of the ISS (NASA Human Spaceflight Gallery, 2008).***

The movement of crew and hardware through the confined spaces of the ISS has been an ongoing topic of concern. As documented in the ISS Life Sciences Crew Comments Database, frequently used ISS translation passages have been blocked by large items, such as stowage or exercise equipment, which has contributed to congestion (figure 10-3). The location of the dining table in a high-traffic area such as the Zvezda service module (pictured in figure 10-2(a) and (b), above), with other colocated habitability hardware, has made translation difficult for crews. These co-location issues are caused by the lack of available habitable volume and resources that is endemic when living in space. This design concept has been suboptimal, however, and will not benefit future space habitat designs, as it presents numerous operational hazards to crews. Indeed, these vehicle design and topology constraints can affect daily tasks, habitability, and overall mission objectives so much that they impede crew safety; clearly, therefore, they must be improved (Category III).

Issues can also arise when safety precautions for the space environment do not take into account pre-flight ground activities. An example of what can occur when on-orbit and pre-flight activities are not well melded took place during the Apollo Program on January 27, 1967, when the Apollo 1 crew initiated what should have been a routine countdown drill. Disaster struck when a flash fire erupted in the command module at the NASA Kennedy Space Center, Pad 34 (figure 10-4). All three of the crew members lost their lives because they were unable to open the hatch and escape the command module to safety (Kranz, 2000). Numerous factors contributed to this incident, including an inadequate hatch design. The hatch, which had been designed to open inward, was impossible for a human to open at the pressure levels that were extant within the vehicle. Procedures or processes had not been put in place to deal with this type of emergency event because little consideration had been given to the risks and hazards that were associated with any of the pre-flight activities, only with those pertaining to space flight. This oversight contributed to the unsafe situation in the capsule and, ultimately, led to the crew members' deaths (Category III).

Figure 10-3. ISS011-E-06401 — ***Astronaut John L. Phillips, Expedition 11 NASA ISS science officer and flight engineer, is photographed among stowage bags in an airlock on the ISS. This photograph illustrates the physical transition/movement difficulties that are encountered on board station (NASA Human Spaceflight Gallery, 2008).***

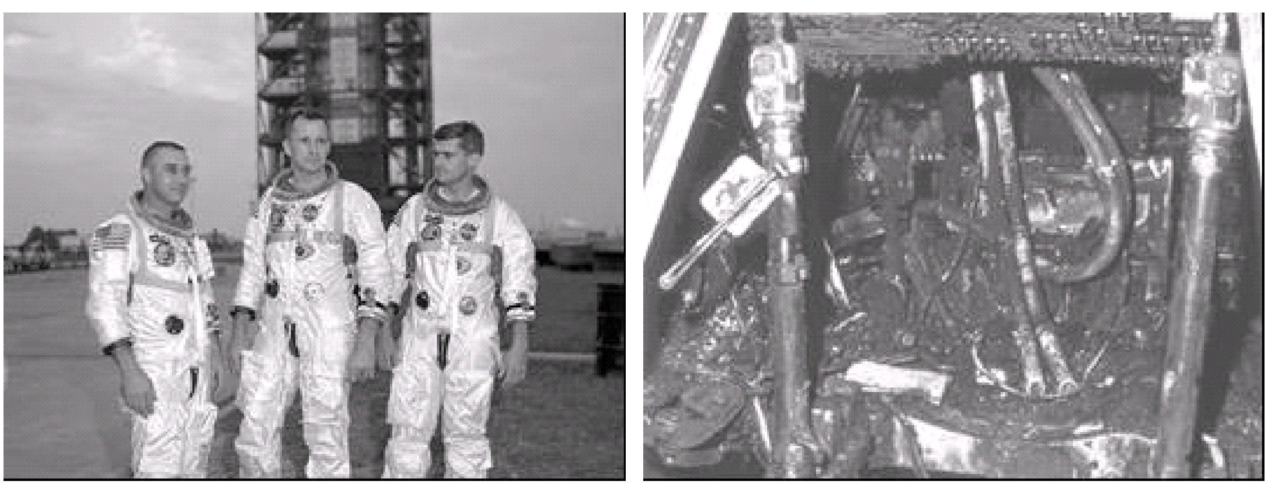


Figure 10-4. ***Apollo 1 crew prior to the tragic fire (left; from left, Virgil I. Grissom, Edward H. White II, and Roger B. Chaffee) and the vehicle after the fire (right) (United States Centennial of Flight Commission, 2003).***

The data that have been amassed on space flight crew postural changes are limited. Currently, space flight researchers are attempting to assess postural changes in zero g and related effects on crew health and safety for future Constellation Program missions. These postural changes directly affect the architectural design constraints and considerations for these future missions in which crew members will experience an increase in height of about 3% during the first day or two of weightlessness. These crew members will retain this increase throughout the mission until they are exposed again to 1g, at which time the process is reversed (*Anthropometric source book*, 1978). Current research indicates that weightless posture differs from any normal 1g posture on Earth, and that the body rebels with fatigue and discomfort against any attempts to force it into 1g postures or appliances that are consistent with 1g postures. The occurrence of crew member height changes was recognized when height data were collected on Skylab 4 and during the Apollo-Soyuz Test Project (ASTP) and were then compared to pre- and post-flight data. The design and usability of any human-machine interface can be affected by changes in the height and length of the trunk (Brown 1975; 1977). Examples of design problems include the design of pressure suits, clothing, workstations, and cockpit seating. New research is planned for upcoming shuttle missions to determine the potential for increased impacts on future vehicle crews from postural limitations on seated height and changes in it, and from the architectural design constraints of the vehicle. These assessments are aimed at increasing safety and efficiency for future missions (Category II).

Usability and design of workspaces, equipment, and tools

The importance of optimized usability and the design of workspaces, equipment, and tools increases in the remote space flight environment. As stated by the authors of the SHFH Risk description, if the workspace, equipment, and tools are not designed to be usable by the full range of crew members and are not properly laid out, the likelihood increases of errors or the inability of the crew to complete a task in a timely manner. Inconsistent design among subsystems and vehicles can also lead to the negative transfer of training, which risks the safety of the crew, and an increased likelihood of errors.

A high level of human-machine interdependence exists in space systems. To promote safe and efficient human factors designs, it is important to consider in the design process not only the biological effects of microgravity, but also the capabilities and limitations of both people and machines. For example, when tools are designed for use during an EVA, the strength that is required to use the equipment should be guided by that of the weakest and smallest individuals (i.e., the 1^{st}-percentile female), as all crew members will have an equal likelihood of needing to use the equipment in an emergency (Category III).

The poor design of workspaces, equipment, and tools on orbit, which will result in poor usability, can lead to performance degradation and reduced situational awareness. As documented in the ISS Life Sciences Crew Comments Database, some ISS hardware items and tools do not have common or consistent interfaces. In addition some hardware items require unique tools, and the metric and English systems are used inconsistently because station hardware and tools are designed by U.S. and International Partners.

Spacesuits are an essential tool for crew members who are living and working in extreme environments such as the moon or Mars as well as for space shuttle and ISS EVAs. Achieving suit comfort has been a challenge for designers. In a study that was conducted in January 2008, data were collected on three subjective measures of comfort in the advanced crew escape suit (ACES), the Mark III suit, and the rear entry ILC Dover suit (REI) (Harvey et al., 2007). With regard to overall discomfort, subjects documented that no matter which spacesuit they were in, they experienced some level of discomfort, and this level of discomfort increased during pressurized testing. Specific anatomical regions where discomfort was noted were the shoulders, back, neck, knees, and lower arms. Discomfort while suited was attributed to the pressure demand regulator in the ACES and to bearing and resting weight in the two planetary suits (i.e., the Mark III suit and the REI). These concerns will figure more prominently for long-duration planetary habitation because of the large number of anticipated EVAs that will be required. Suit discomfort can reduce the safety and efficiency of all aspects of crew performance (Category II).

Stowage is a critical component of the usability and design of space flight vehicle and habitat workspaces (Clark and Allen, 2008). On-orbit stowage includes not only the location of, but also the organization of, stowed items. Operations are impeded if stowed items cannot be easily located or identified (figures 10-5 through 10-7). With increased and accumulating stowage on board the ISS, there has been a need to stow items in front of panels and in translation paths, resulting in the crew members' reduced ability to access items quickly. In addition, cable routing blocks access to panels and stowage locations.

Figure 10-5. ***S118-E-07630 — Astronaut Alvin Drew, STS-118 mission specialist, moves a stowage container through the Destiny laboratory of the ISS while Space Shuttle*** **Endeavour** ***remains docked with the station (NASA Human Spaceflight Gallery, 2008).***

Figure 10-6. ISS010-E-25228 — ***This view shows supplies and equipment stowed in the functional cargo block (FGB) or Zarya photographed by a crew member on the ISS. (NASA Human Spaceflight Gallery, 2008).***

Figure 10-7. ISS016-E-028889 — ***Cosmonaut Yuri I. Malenchenko, Expedition 16 flight engineer representing the Russian Federal Space Agency, works in the Unity node of the ISS while Space Shuttle*** **Atlantis** ***(STS-122) is docked with the station. (NASA Human Spaceflight Gallery, 2008).***

ISS accessibility problems are caused both by obstructions and by the design and integration of hardware (Clark and Allen, 2008). The interior components of the U.S. segment of the ISS are grouped into a series of "racks" that individually rotate, or tip over, to provide crew access to the rack utility connections and the module wall. However, crew feedback has indicated that rotating the racks is not an effective way to access utilities and connectors in the microgravity environment on station. The clearance that is required for human accessibility has been repeatedly cited as an issue in rack rotation capability. The design of the panels and drawers with these racks has compromised crew accessibility because many of them "stick" on orbit because the design does not operate as intended in zero g, or too many items are placed in the stowage locations and are not organized to afford easy operation.

Finally, overall topology of workspaces has negatively affected crew accessibility. As an example, the U.S. cycle ergometer blocks access to the U.S. Laboratory window. As physical and visual access to on-board windows is very important to crew members for their mental health and overall judgment of habitability, restricted access and blocked translation paths contribute negatively to the overall safety and efficiency of the crew, especially in the event of an emergency (Category III).

The ISS on-board stowage accumulation has also been exacerbated by the buildup of packing materials that arrive with each shipment (by either space shuttle or a resupply vehicle, such as the Russian Progress module) (Baggerman et al., 2004). The limitations that are associated with the ability to dispose of packing materials on station result in excessive amounts of space being used to stow waste. The amount of stowage on board the ISS has increased to the point that all of the designated stowage areas are full and items are now being stowed in areas that were intended for habitability and work-related functions. Items are now stowed in passageways as well as in front of other stowage areas. In some instances, the stowage violates the allowable limits requirements that were originally set for the habitable volume areas. The result of this is that when crew members are searching for items, they must move many other stowed items out of the way to gain access to the place in which a desired item is located. During some ISS Expeditions, stowage has been located in the translation aisle, thereby blocking the emergency fire ports. This specific issue serves as an example of the risk that excessive stowage can impose on crew safety (Category III).

Balancing the launching of ISS supplies (manifest) with the ability to dispose of waste and to return items to Earth (down mass) is necessary to maintain habitable conditions on the ISS (Baggerman et al., 2004). The stowage situation became a habitability issue because of an imbalance between the space shuttle launch and return mass limits due to the grounding of the shuttle fleet after the *Columbia* accident and the reluctance of ISS Program personnel to dispose of unused hardware and supplies. As the amount of on-board stowage has, at times, exceeded the allowable ISS requirements for acceptable levels of stowage in the habitable volume, stowage levels are constantly tracked and evaluated. Over time, the on-board inventory of supplies (e.g., clothing and hygiene supplies) has increased, and the manifesting of these supplies still continues. Each ISS Expedition crew member brings a selection of personal items with him or her to station, and at the end of that crew member's stay the unused items remain. This increase in inventory contributes to crew safety risks, as ample stowage space is not available to accommodate placement of items outside of the habitable volume and translation paths. As the inventory management function has improved and the manifesting process has been streamlined, this situation has improved somewhat; stowage nevertheless continues to be a problem due to the lack and inconsistent nature of disposal capability due to space shuttle flights and inconsistent practices for tracking hardware and supplies (Category III).

Computer-based Simulation Information

Understanding human integration with systems and identifying risks that may be inherent in a concept or a design is often achieved via computer-based simulation. Computer-based simulation tools have multiple uses, including detection of potential risks to humans that are associated with reduced safety and efficiency due to inadequately designed space vehicles, environments, tools, or equipment. Computer-based simulation and virtual environments create a representation of the real world, and the user interacts with this representation with the aid of head-mounted displays, data gloves, and three-dimensional audio, haptic, or tactile feedback. Such environments can be used for training or, perhaps, interacting with prototypes that do not yet exist in the real world.

In the 1990s, NASA and the Federal Aviation Administration (FAA) engaged in several joint research efforts with the goal of providing safer, faster, and more fuel-efficient routing operation in flight management through use of automation in air traffic control (Pisanich and Corker, 1995). It was thought that integrating automation technologies into the air traffic control system could optimize routing, sequencing, and scheduling in the terminal areas and, ultimately, improve efficiency while relaxing constraints during flight to accommodate user-preferred routing and schedules. Man-machine Integration Design and Analysis System (MIDAS) was adapted to model a predictive flight crew performance (figure 10-8) that focused on predicting the performance of a two-pilot flight crew responding to information that was generated by an automated air traffic control system, the Center Terminal Radar Approach Control (TRACON) Automation System (CTAS).

During the course of research, experimenters conducted two computer simulations. The first of these employed a model of top of descent (TOD). This model was developed with the goal of determining an optimal range of time in which the CTAS descent clearance would be issued so that the aircrew would be likely to accept the clearance and enact it using flight deck automation rather than by manually commanding the descent. This model confirmed that as the TOD point draws closer, the aircrew will select the less-automated alternative mode of control. In this study, as the aircraft approached within 5 to 8 miles of the CTAS-required TOD point, the number of successes in any clearance compliance was reduced significantly. It was found that multiple simulated trials could be conducted without compromising human safety when determining the optimal range of time in which to issue CTAS descent clearance. Moreover, multiple scenarios could be tested that did not require the use of an aircraft, and the aircrew's trust in the automation could also be determined. Results of the study assisted designers in integrating automation technologies into the system to improve crew efficiency by optimizing routing, sequencing, and scheduling. This provides evidence that inadequately designed equipment could lead to a risk of reduced safety and efficiency (Category II).

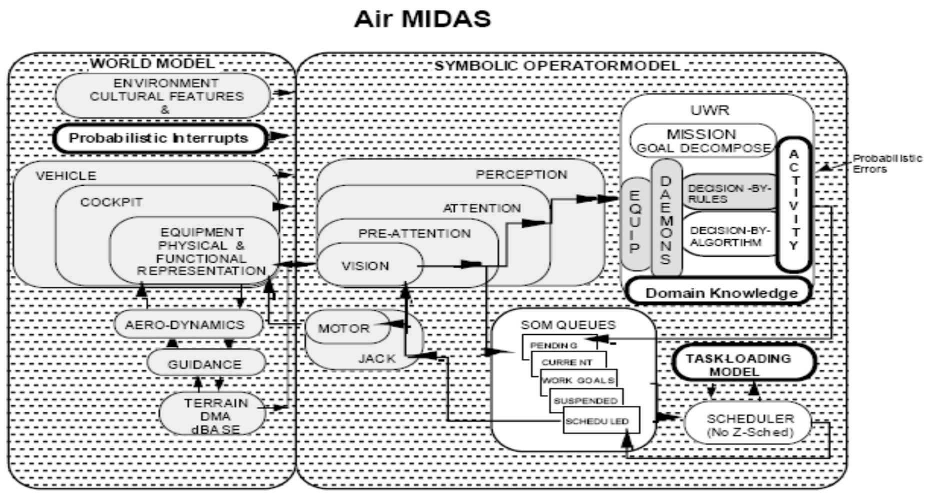


Figure 10-8. ***Full MIDAS closed-loop model (Pisanich and Corker, 1995).***

Risk in Context of Exploration Mission Operational Scenarios

Future Exploration mission durations will substantially lengthen. During this extended timeframe, crews will face the challenges of physical deconditioning, prolonged isolation and confinement, significant communication latencies, environmental stressors, and increased responsibility and autonomy. Effective human-centered design techniques for vehicles, habitats, and missions allow Exploration mission operational scenarios to be managed and controlled. For further information, see Chapter 9 of this report.

Human-centered design must be implemented in all aspects of the design process to mitigate or prevent space human factors engineering risks from occurring and specifically to ensure the safety and efficiency of the crew. Designing for reduced gravity will be critical. Lunar and martian environmental conditions – air quality, dust, radiation exposure, and lighting – must be addressed. The interior configuration of the spacecraft must support expected crew tasks. Hardware commonality and standardization will support interchangeability and reduce the amount of time that is needed for training. Spacecraft designers need to ensure that appropriate spares and stowage volumes are available and can be accessed in a timely manner. A reduction in required maintenance and interface with complex systems should also be implemented.

Conclusion

The risk of reduced safety and efficiency due to inadequately designed vehicle, environment, tools, or equipment stems from a broader cause of human error – the lack of human-centered design, which requires a focus on the user throughout the design process. Good human-centered design practices will result in improved efficiency of operation and safety of all system components, including the human, and should reduce the life-cycle cost of the project. The evidence that is discussed in this chapter identifies concerns that are associated with the risk. To alleviate these concerns, knowledge gaps, or "holes," and future research directions have been identified. Some of these knowledge gaps are related to poorly designed hardware, software, environments, and habitats as well as the lack of appropriate design considerations, guidelines, and countermeasures for systems on future vehicles.

The human-machine system emphasizes the importance of the human as the central focus of the human-centered design process. This focus includes consideration for human capabilities, limitations, and interaction with automation and hardware. Knowledge gaps, or "holes," that are related to the lack of an integrated system design approach for environmental and architectural design and usability and the design of workspaces, equipment, and tools must be addressed to ensure that quality standards, requirements, tools, and techniques are developed to allow positive crew-system integration and interaction to occur and, ultimately, mission success.

References

Baggerman SD, Rando C, Duvall LE. (2004) Habitability and human factors: lessons learned in long duration spaceflight. In: Proceedings of the American Institute of Aeronautics and Astronautics Space 2004 Conference Exhibit. San Diego, Calif., Sep 2004.

Brown J. (1975) ASTP002: *Skylab 4 and ASTP crew height*. Retrieved Dec 28, 2007 from the following Website: http://lsda.jsc.nasa.gov.

Brown J. (1977) Crew height measurement. In: Nicogossian A (Ed.), *The Apollo-Soyuz Test Project medical report*. NASA, Washington, D.C., pp. 119–121.

Clark JB, Allen CS. (2008) Acoustics issues. In: Barratt MR, Pool SL (Eds.), *Principles of clinical medicine for spaceflight*. Springer-Verlag, N.Y., pp. 521–534.

Goodman JR. (2000) International Space Station acoustics. *J. Acoust. Soc. Am.,* 108(5):2475.

Harvey C, Jones J, Whitmore M, Gernhardt M. (2007) *Wearability, comfort and field of view findings from the integrated launch suit test*. TP-2007-214754. NASA Johnson Space Center, Houston.

Kranz G. (2000) A fire on the pad. In: *Failure is not an option*. Simon & Schuster, N.Y., pp. 191–207.

NASA. Human Spaceflight Gallery [photographs on the Internet]. Retrieved Jan 26, 2008 from the following Website: http://spaceflight.nasa.gov/gallery/index.html.

Pisanich GM, Corker KM (Eds.). (1995) A predictive model of flight crew performance in automated air traffic control and flight management operations. Proceedings of the 8th International Symposium on Aviation Psychology, Columbus, Ohio, Apr 24–27, 1995.

Rando C, Baggerman SD, Duvall LE. (2005) Habitability in space. In: Proceedings of the Human Factors and Ergonomics Society 49th Annual Meeting, Aerospace Systems. Human Factors and Ergonomics Society, Orlando, Fla., Sep 26–30, 2005, pp. 5–9.

Staff of Anthropology Research Project (Eds.) (1978) *Anthropometric source book; Vol. I: Anthropometry for designers*. NASA 1024. Webb Associates, Yellow Springs, Ohio.

United States Centennial of Flight Commission. (2003) *Born of dreams – inspired by freedom*. Retrieved Jan 28, 2008 from the following Website: http://www.centennialofflight.gov.

Acknowledgments

Immanuel Barshi, Ph.D., Linguistics and Cognitive Psychology; Senior Principal Investigator, Human System Integration Division; NASA Ames Research Center, Moffett Field, Calif.

Carlton Donahoo, M.A., Human Factors; Usability Testing and Analysis Facility Human Factors Engineer, Habitability and Environmental Factors Division; NASA Johnson Space Center, Houston.

Michael Feary, Ph.D., Human Factors Engineering; Automation Design and Analysis; Research Psychologist; Ames Research Center, Mountain View, Calif.

Alicia Foerster, B.S., Marine Biology; Project Manager, SHFH Element, HRP; NASA Johnson Space Center, Houston.

Keith V. Holubec, B.S.; Project Manager, SHFH Element, HRP; NASA Johnson Space Center, Houston.

Victor Ingurgio, Ph.D., Experimental Psychology; Senior Human Factors Design Engineer for the Anthropometry and Biomechanics Facility; NASA Johnson Space Center, Houston.

Robert S. McCann, Ph.D., Cognitive Psychology; Human-System Interface Design and Evaluation; Group Lead, ISIS Lab; NASA Ames Research Center, Moffett Field, Calif.

Cindy Rando, M.S., Human Factors; ISS Flight Crew Integration Human Factors Engineer, Habitability and Environmental Factors Division; NASA Johnson Space Center, Houston.

Dane Russo, Ph.D., Experimental Psychology; Space Systems Development and Project Management; SHFH Element Manager, HRP; NASA Johnson Space Center, Houston.

Barry Tillman, M.S., Systems and Industrial Engineering, B.A., Psychology; Senior Human Factors Engineer, Habitability and Human Factors Branch; NASA Johnson Space Center, Houston.