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## The Issues and Complexities Surrounding the Future of Long Duration Spaceflight

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ASCI 691 Graduate Capstone Comprehensive Examination  
The Issues and Complexities Surrounding the Future of Long Duration Spaceflight  
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### Abstract

The Comprehensive Exam put forward by this proposal is intended to address the learning objectives covered by the Master of Aeronautical Science Degree with specializations in Aviation Aerospace Safety Systems and some limited aspects in Human Factors in Aviation Systems. This will be accomplished by researching the following topics: effects of long duration spaceflight on crew performance and functioning and the steps that should be taken to enable long term spaceflight mission crews in lieu of accomplishing important missions; a human factor analysis should current human-machine design interfaces be enhanced to make manual rendezvous and docking in space easier to perform. This exam will also inspect extensive analysis concerning the human factor implications involved in manually controlled rendezvous and docking missions in space. Furthermore, an evaluation will be made on how emerging virtual modeling technology can aid in solving ergonomic design problems of the International Space Station. Finally, this research will provide a discussion concerning the potential long term consequences of the enormous amount of debris in Earth orbit and strategies for debris mitigation followed by an analysis concerning how microgravity induced physiological issues are counteracted for future long duration space missions. The researcher will utilize mixed research methodology by investigating the relationship and correlation between the results obtained using inferential statistics, such as linear regressions.

*Keywords:* National Aeronautics and Space Administration (NASA), microgravity, spaceflight, International Space Station (ISS), European Space Agency (ESA), manual rendezvous and docking (manual RVD), space physiology, space psychology, ergonomic design, space debris, human-machine design interface, United States Strategic Command (USSTRATCOM), human-out-of-the-loop (HOOTL), Active Debris Removal (ADR)

## Proposal

### Comprehensive Exam Question #1

**Statement of the question:** “What are the effects of long duration spaceflight on crew performance and functioning, and what should be done to facilitate long-term spaceflight missions?”

What is known at present is that crew performance deteriorates over time in weightless and microgravity environments and a number of physical and psychological problems can develop to the point where crews may become dysfunctional. For example, Vakoch (2011) emphasizes that “It is a mistake to try to assess and maximize performance without understanding group dynamics, the effects of isolation and confinement or the environment in general on inhabitants” (p. 59). Moreover, many of the studies to date have produced conflicting results based on the types of tests that have been used (Vakoch, 2011). In this context, it is required to identify the relevant human behaviors and limitations that can provide the framework needed to reach appropriate conclusions regarding the effects of long duration spaceflight on crew performance and functioning. Additionally, it is also required to identify the steps that should be undertaken to mitigate the issues in the future in regard to the type of monitoring required to analyze the psychological and physiological status of all crew aboard a spacecraft. It would also analyze the type of personalized support measures that are required to reduce these effects that limit the spaceflight and the crew performances.

**Program outcome that will be addressed by this question:**

**Program Outcome #3:** *The student will be able across all subjects to use the fundamentals of human factors in all aspects of the aviation and aerospace industry, including*

*unsafe acts, attitudes, errors, human behavior, and human limitations as they relate to the aviator's adaption to the aviation environment to reach conclusions.*

This program outcome will be addressed using a content analysis of relevant studies to identify fundamental human factors that are involved in long duration spaceflight. Besides, it will also address what and how human behaviors and limitations can exacerbate these problems.

This issue will be addressed by identifying *unsafe acts* that are caused by the physiological and psychological effects of long duration spaceflight drawing on studies by Morphew (2001), Reschke, M. F. and Kozlovskaya (2017), Zhang et al. (2015), among others.

This issue will be addressed by determining how crew *attitudes* can be positively and negatively affected by long duration space flight using the above-listed studies as well as scholarly texts such as Buckey (2006) and Vakoch (2011).

Like the unsafe acts issue and using the same resources, this issue will be addressed by identifying past *errors* that have been made on prolonged space missions as well as the potential for catastrophic errors on long duration space flights due to diminished crew performance and functioning.

Similar to the attitudes issue, addressing this issue will involve a content analysis concerning the psychological effects of long duration space flights and how they affect *human behavior* including recent studies by Zhang et al. (2015), Zhu et al. (2015) and Reschke and Kozlovskaya (2017).

This issue will be addressed by identifying what types of *human limitations* such as the high maintenance requirements and vulnerability to critical illnesses during long duration space missions and what steps can aid in mediating these limitations drawing on the resources used for the human behavior component.

**Program outcome #4:** *The student will be able to develop and/or apply current aviation and industry-related research methods, including problem identification, hypothesis formulation, and interpretation of findings to present as solutions in the investigation of an aviation/aerospace-related topic.*

**Research methodology** used for this program outcome will be qualitative. Although NASA is currently conducting field tests concerning the effects of long duration spaceflight on humans and has collected statistical data concerning these effects with 18 astronauts and cosmonauts beginning with the 34S mission and ending with the 41S mission, this data has not yet been released (Reschke & Kozlovskaya, 2017).

A qualitative research method will be used to develop a timely and informed answer to this research question as well as to identify the primary problems, formulate a hypothesis and provide an interpretation of these findings. The qualitative data used for this program outcome will include an analysis of the known effects of long-term spaceflight on human performance and functioning which include exhaustion, fatigue, emotional instability, feelings of tiredness, sleeplessness, and a diminished capacity for work (Morpheus, 2001).

The **primary research question** for this program outcome is, “What are the effects of long duration spaceflight on crew performance and functioning.” A **secondary research question** for this program outcome is, “What should be done to facilitate long-term spaceflight missions?”

The **problem** is the physiological and psychological effects that long duration spaceflight can have on the individuals involved in space travel to include fatigue, insomnia, and overall diminished work capacity.

The **HI** states that long duration spaceflight is negatively affecting space crew performance and their ability to remain mission functional in the microgravity environment.

The *H0* states that no negative effects caused by long duration spaceflight in a microgravity environment on crew performance and functioning exist.

The *interpretation of the findings* will emerge from the research into these primary and secondary questions. Moreover, it will be accomplished through systematic analysis of the research that has been collected to date regarding the effects of long duration spaceflight on crew performance and functioning to identify opportunities to improve training and minimize these adverse effects to the maximum extent possible.

### **Comprehensive Exam Question #2**

**Statement of the question:** “How should current human-machine design interfaces be enhanced to make manual rendezvous and docking in space easier to perform?”

Manual rendezvous and docking missions in space are fraught with danger and demand sophisticated human-machine interfaces to succeed (Roesler, 2009). According to Petit, Marchand and Kanani (2011), “A space rendezvous consists in the approach of a chaser spacecraft towards a target spacecraft, from detection of the target (if necessary) until docking on the target” (p. 619). The chaser spacecraft is navigated to the target spacecraft by constantly measuring their respective positions until docking is achieved (Petit et al., 2011). To facilitate this operation, there have been some computer vision technologies that have been developed specifically for rendezvous mission proximity estimates (Petit et al., 2011).

Given the rapid increase in the complexity of space vehicles, it is reasonable to suggest that current human-machine design interfaces may lack the ease of use considerations required for manual rendezvous and docking in space. At present, manual rendezvous and docking missions typically require the use of different types of navigation sensors that may eventually allow for autonomous rendezvous missions in the future (Dennehy, 2016). For instance,

Dennehy (2016) reports that “Autonomous rendezvous could also lead to lower operational costs. More autonomy may eventually reduce the workload for on-ground crews or the pilots and crews in the spacecraft itself” (p. 3). Currently, though, manual rendezvous and docking maneuvers in space remain a challenging enterprise for crewmembers (Du, Zhang, Tian, Huang, Wu & Zhang, 2015), creating a vital need for enhanced human-machine interfaces.

**Program outcomes that will be addressed by this question:**

**Program Outcome #1:** *Students will be able to apply the fundamentals of air transportation as part of a global, multimodal transportation system, including the technological, social, environmental, and political aspects of the system to examine, compare, analyze, and recommend conclusions.*

The **global** aspect of this program outcome will be addressed by comparing the results of the studies of human-machine interfaces for manual rendezvous and docking missions in space.

The **multimodal** aspects will be addressed by synthesizing the results of simulated manual docking studies in the U.S., Europe and China and related scholarly articles.

The **technological** aspect of this program outcome will be addressed by using a quantitative research method. The quantitative data for this question will draw on the results of simulated manual rendezvous and docking (manual RVD) studies designed and developed by technicians at the China Astronaut Research and Training Center.

The **social** issues that are involved in this program outcome include cross-cultural differences that may affect the utility and operation of human-machine interfaces drawing on Geert Hofstede’s cultural dimension analysis and studies of cross-cultural constraints in using existing human-machine design interfaces drawing on other various studies.



The *environment* aspect will be addressed by a review and synthesis of the literature concerning what factors should be taken into account when designing human-machine interfaces for weightless environments such as the study by Wang et al. (2014).

Finally, the *political* issues concerning human-machine interfaces will be addressed by reviewing past international collaborative efforts to develop human-machine interfaces and how conflicting opinions were resolved using studies of the development and construction as seminal sources.

**Program Outcome #2:** *The student will be able to identify and apply appropriate statistical analysis, to include techniques in data collection, review, critique, interpretation, and inference in the aviation and aerospace industry.*

The quantitative data for this question will draw on the results of simulated manual rendezvous and docking (manual RVD) studies designed and developed by technicians at the China Astronaut Research and Training Center. A quantitative *research method* will be used to address this program outcome. The *statistical analysis* method utilized will be a linear regression of the results of these studies. Furthermore, analysis of the study's that were carried out by the China Astronaut Research Training Center will make to include Guilford-Zimmerman Spatial Orientation Test and Guay's Visualization of Viewpoints tests most of these are used to measure astronaut spatial orientation ability (Wang et al., 2014). *Interpretation* of these analyses will identify relationships between spatial orientation ability and crew manual RVD performance.

**Program Outcome #3:** *The student will be able to use the fundamentals of human factors in all aspects of the aviation and aerospace industry, including unsafe acts, attitudes,*

*errors, human behavior, and human limitations as they relate to the aviators adaptation to the aviation environment to reach conclusions.*

This program outcome will be addressed using a review of qualitative studies concerning relevant human factors that have been experienced in manual rendezvous missions in space, including unsafe acts and attitudes, errors of commission and omission as well as how human-machine interfaces affect human behavior in space and how human imitations affect their effectiveness as follows.

The *unsafe acts* aspect of the program outcome will be addressed by determining how current human-machine design interfaces can result in unsafe acts in performing manual rendezvous missions in space utilizing studies from Gravitational and Space Biology Bulletin, and Advances in Space Research.

The *attitudes* issue will be addressed through a review of published interviews and studies concerning crew member attitudes about current human-machine interfaces in space habitats. For instance, the International Space Station (ISS) utilizing NASA research and scholarly journals from Personal and Ubiquitous Computing.

This factor will be addressed by identifying how current human-machine design interface can cause *errors* by crew members during manual docking missions using relevant studies to include Frontiers of Psychology and many others.

This issue will be addressed through a review of relevant studies concerning human behavioral constraints in using current human-machine design interfaces for manual docking missions including the resources used for the *human behavior* factor as well as empirical observations from crew members published by various space agencies.

Finally, the factor will be addressed by identifying opportunities to improve current human-machine design interfaces to account for known *human limitations* in space, including those published by NASA and the European Space Agency.

**Program Outcome #4:** *The student will be able to develop and/or apply current aviation and industry-related research methods, including problem identification, hypothesis formulation, and interpretation of findings to present as solutions in the investigation of an aviation/aerospace-related topic.*

This program outcome will be addressed using qualitative and quantitative *research methods*. The qualitative approach will draw on recent studies concerning human-machine design interfaces and what steps have been shown to facilitate manual rendezvous in space. The *problem* identification for this program outcome relates to the *primary research question*, “How should current human-machine design interfaces be enhanced to make manual rendezvous in space easier to perform?” A literature review and synthesis will be used to formulate a hypothesis concerning the potential for improvements in human-machine interfaces in the foreseeable future. These qualitative findings will be interpreted to answer the primary research question as well as a *secondary research question*, “How can current human-machine design interfaces be improved to facilitate manual rendezvous and docking in space?”

The *problem* is human-machine interfaces currently being utilized might not have been designed with a human factors perspective and there might be a necessity for system enhancement for the 21<sup>st</sup>-century astronaut performing manual rendezvous and docking maneuvers with the current highly sophisticated technology.

The ***H1*** questions if a necessity has risen to enhance current human-machine interface methodology and technology being utilized for manual rendezvous and docking of space vehicles as defined in PO#2.

The ***H0*** states that the current methodology and technology being utilized for manual rendezvous and docking for space vehicles doesn't require enhancement as defined in PO#2.

The ***interpretation of findings*** from this quantitative data will be achieved by analyzing simulated manual rendezvous and docking studies by the China Astronaut Research and Training project. The findings that emerge from this analysis will be used to provide recommendations concerning ways to enhance current human-machine interfaces to facilitate manual rendezvous and docking for in-orbit space operations. The interpretation of the qualitative findings will be presented as a synthesis and include current recommendations by experts in the field.

### **Comprehensive Exam Question #3**

**Statement of the question:** "How can emerging virtual modeling technology help solve ergonomic design problems of the International Space Station?"

The International Space Station (ISS) is far larger and massive than any other manned presence in space, with an array of solar panels that stretches nearly an acre and a mass of nearly one million pounds (Newman, 2000). Missions on the ISS typically last about 6 months, and the comfort of crew members during these missions represents a vital part of helping them remain effective (International Space Station, 2017). In this regard, Schlacht and Birke (2011) report that "Today, well-being, comfort and human factors are becoming important in space missions. The International Space Station was designed mainly according to the logic of short space missions (SDM) (less than 2 weeks" (p. 498).

According to Schlacht and Birke (2011), the utilitarian nature of space habitats such as the ISS may adversely affect crew members' comfort and performance. For instance, these researchers point out that, "In the ISS, the interior is optimized and conceived as a working interface. Racks and space furniture have an interface composed of cables, instruments, experiment equipment and storage compartments" (Schlacht & Birke, 2011, p. 497).

An early study by Gellerman concluded that from an ergonomic perspective, "Basically, the ultimate comfort of the user is key" (Gellerman, 1994, p. 15). Another early study by Vidov and Alexander (1992) noted that virtual modeling technology was already being used to identify optimal ergonomic design elements. In sum, the potential value of virtual modeling technology for ergonomic design in space applications is enormous (Palamidese, 1999). Virtual modeling technology now provides researchers with the ability to replicate the three-dimensional environment. In this environment, the crew members live and work in space, an attribute that is especially useful since astronauts operate in their entire environment without regard an "up or down" orientation (Schlacht & Birke, 2011).

While the environment aboard the ISS provides crew members with a number of advantages, there are some design issues in place that may become detrimental to crew member performance. In this regard, Newman (2000) emphasizes that "Human presence on space missions offers many advantages to ensure mission success: flexibility and dexterous manipulation, human visual interpretation and cognitive ability, and real-time approaches to problems. However, there are factors that may degrade human performance" (p. 35). Factors that have been shown to adversely affect human performance in space include the encumbering effects of pressure suits, insufficient work areas, pre-breathing requirements, and suboptimal tool

or task design (Newman, 2000). As a result, there are several opportunities for solving the ergonomic design problems of the ISS using virtual modeling technology.

**Program outcomes that will be addressed by this question:**

**Program Outcome #3:** *The student will be able across all subjects to use the fundamentals of human factors in all aspects of the aviation and aerospace industry, including unsafe acts, attitudes, errors, human behavior, and human limitations as they relate to the aviators adaption to the aviation environment to reach conclusions.*

This program outcome will be addressed qualitatively using a literature review and synthesis to determine salient fundamental human factors that must be taken into account in the ergonomic design of space station tools, facilities and equipment and how human attitudes and errors can be minimized through effective ergonomic design. In addition, relevant human behaviors and limitations that influence ergonomic design as follows.

The qualitative analysis will address this issue of *unsafe acts* by identifying any existing ergonomic design flaws that are unique to microgravity environments that can cause unsafe acts by crew members. It could be resolved using virtual modeling technology drawing on studies such as Newman (2000) and Schlacht and Birke (2011) as well as trade journals that specialize in visual model technology.

This factor will be addressed by evaluating the effects of crew member *attitudes* concerning the current ergonomic design used on the ISS on their performance and functioning that could be resolved using virtual modeling technology. For instance human-out-of-the-loop (HOOTL) and drawing on relevant studies published by participating nations in the aerospace field.

Like the unsafe acts component, this element will be addressed by identifying any ergonomic design flaws in microgravity environments that can result in human *errors*. These errors could be resolved using virtual modeling technology drawing on recent studies of the current ergonomic design of the ISS by NASA.

The *human behavior* element will be addressed by determining how the physical movements of crew members in space habitats differ from gravity environments. It will identify opportunities to improve current designs using virtual modeling technology using studies such as Wilkinson (2015) and published empirical observations by ISS crew members.

Finally, the *human limitations* factor will be addressed by determining if current design features are exacerbating or mitigating human physiological and psychological limitations and ways to improve currently utilized virtual modeling technology. Numerous studies will be used such as Zhang et al. (2015) and relevant trade journals specializing in this technology.

**Program Outcome #4:** *Fundamentals of research and problem solving methods. The student will be able to develop and/or apply current aviation and industry-related research methods, including problem identification, hypothesis formulation, and interpretation of findings to present as solutions in the investigation of an aviation/aerospace-related topic.*

**Research Methodology** for program outcome will also be addressed using a qualitative approach that provides a systematic review of the literature to identify the problem, formulate a corresponding hypothesis concerning best ergonomic design practices and provide an *interpretation of the findings* concerning how emerging virtual modeling technology can help solve ergonomic design problems of the International Space Station (ISS).

The ***problem*** arises with the current state of the art virtual technology possibly not being exploited to its full extent in regards to solving major ergonomic issues experienced by astronauts aboard the International Space Station.

The ***H1*** states, virtual modeling using anthropometric data and astronaut behavioral traits can be utilized to solve many of the ergonomic design faced aboard the ISS and this could also be used to evaluate astronaut readiness and performance in a space environment.

The ***H0*** states that virtual modeling using anthropometric data and astronaut behavioral traits if utilized would not solve any of the ergonomic design issues faced aboard ISS hence it wouldn't aid in the evaluation of astronaut readiness and performance in a space environment

**Program outcome #9:** *The student will investigate, compare, contrast, analyze and form conclusions to current aviation, aerospace, and industry- related topics in safety systems, including systems safety, industrial safety, accident investigation and analysis, transportation security, airport safety and certification, safety program management, and aviation psychology.*

This program outcome will be addressed by ***investigating and analyzing*** the current virtual modeling technologies to compare and contrast their effectiveness and ease of use to form relevant conclusions concerning the ***primary research question*** for these program outcomes which are, "How can virtual modeling technology be applied to ergonomic design problems? The ***secondary research question*** is, "What ergonomic problems are most commonly experienced at present in the International Space Station?" Aspects of ***safety program management*** will be addressed by exploring the three tiered approach modeled for the ISS to ensure the safety of integrated operations in cases of visiting spacecraft. ***Transportation security*** very significant to ergonomic design and it cannot be disregarded, but in the case of the ISS, an orbiting spacecraft, this has to be addressed singularly. Security compromise of ground control



systems is a serious threat to the ISS and an analysis of what the Mission Control Center's Computer Safety Work Group has designed to combat these possible IT breaches is pertinent to the overall design of the spacecraft.

The *airport safety and certification and aviation psychology* aspects will not be covered by this outcome.

#### **Comprehensive Exam Question #4**

**Statement of the question:** How should current debris mitigation methods change to prevent future catastrophic collisions? Does a correlation exist between an increase in space debris and potential collisions within the next 200 years, based on projected satellite deployments in low Earth orbit? What are the implications that space debris plays in today's geopolitical environment?

One of the most serious problems facing space travel today is the amount of debris that is in Earth orbit today. According to estimates published by NASA, there are more than a half million pieces of debris the size of a marble or larger as well as 20,000 pieces of orbital debris that are larger than a softball that is monitored during the Earth orbits, and this debris travels at sufficient velocity (17,500 mph) to cause catastrophic damages to spacecraft or satellites (Space debris and human spacecraft, 2017). Indeed, it is surprising that there have only been three documented accidental collisions between catalogued space objects from 1991 to 2005. According to Liou and Johnson (2006), "The most recent (January 2005) was a 31-year-old U.S. rocket body and a fragment from the third stage of a Chinese CZ-4 launch vehicle that had exploded in March 2000" (p. 343).

A number of studies performed during the period from 1991 through 2001 indicated that even if all launches were stopped today, the amount of orbital debris will continue to increase

due to expected increase in collisions between orbital debris. In this regard, Lion and Johnson (2006) conclude that “Even if launch operations were to cease today, the population of space debris would continue to grow. Further, proposed remediation techniques do not appear to offer a viable solution” (p. 341). Given the potential for orbital debris to damage satellites and cause human casualties in space, NASA remains vigilant in tracking this debris, a term that refers to any artificial object in space that is no longer functioning in a useful fashion, including abandoned launch vehicle stages, nonfunctional spacecraft, mission-related debris and fragmentation debris (Space debris and human spacecraft, 2017).

**Program outcome that will be addressed by this question:**

**Program Outcome #2:** *The student will be able to identify and apply appropriate statistical analysis, to include techniques in data collection, review, critique, interpretation, and inference in the aviation and aerospace industry.*

A quantitative and qualitative **research method** will be used to address this program outcome. The **statistical analysis** method utilized will be nominal distribution models of predicted catastrophic collisions using the current estimated debris population from conjunction assessments retrieved by NASA from the Joint Space Operations Center at U.S. Strategic Command (USSTRATCOM). An analysis of cumulating orbital debris will be made to compare if active debris removal is the optimal solution or if non-mitigation methods should be taken in lieu of explaining the importance of stabilizing this environment. The quantitative data will be collected from recent studies concerning estimated spatial density distributions for objects 10 cm and larger, for three different years, 2004, 2014 and future projections up to 2210 as well as the effective number of objects, 10 cm and larger, between 900 and 1000 km altitudes based on the LEO to GEO Environment Debris model (LEGEND) simulation (Liou & Johnson, 2006). In

addition, a qualitative *review and critique* and statistical tables of the primary findings that emerge from a review of recent studies concerning orbital debris mitigation strategies will also be used to address this program outcome.

**Program Outcome #4:** *The student will be able to develop and/or apply current aviation and industry-related research methods, including problem identification, hypothesis formulation, and interpretation of findings to present as solutions in the investigation of an aviation/aerospace-related topic.*

A *mixed research method* will be used for this program outcome to explain and identify the extent of the orbital debris problem, formulate a hypothesis concerning the potential increase in these objects over the next century and provide an interpretation of these findings to identify optimal solutions. The *primary research question* for these program outcomes is, “How should current debris mitigation methods change to prevent future catastrophic collisions?” The *secondary questions* for these program outcomes are, “Does a correlation exist between an increase in space debris and potential collisions within the next 200 years, based on projected satellite deployments in low Earth orbit?” and, “What are the implications that space debris plays in today’s geopolitical environment?” The analysis of the findings will be applied to answer the primary research question as well as the secondary research questions.

The *problem* is current debris population in the LEO region has reached the point where the environment is unstable and collisions will become the most dominant space debris-generating mechanism in the future.

The *HI* questions if a correlation exists between an increase in space debris and potential collisions within the next 200 years, based on projected satellite deployments in low Earth orbit as defined in PO#2.

The ***H<sub>0</sub>*** states that there is no correlation between an increase in space debris and potential collisions within the next 200 years, based on projected satellite deployments in low Earth orbit as defined in PO#2.

### **Comprehensive Exam Question #5**

**Statement of the question:** “How can microgravity induced physiological issues to be counteracted to support future long duration space missions?”

There is a growing body of research concerning the types of physiological problems that are typically experienced in weightless and microgravity environments, and there is a general consensus that additional space physiology research is needed today (Buckey, 2006). The studies to date confirm the rapid loss of bone in space as well as a corresponding risk for the formation of kidney stones, but these studies have reported mixed results concerning the most efficacious interventions that can be used in space (Buckey, 2006). Likewise, a study by Zhu, Wang and Liu (2015) found that some astronauts and cosmonauts have experienced cardiovascular problems during and following space missions. For example, Zhu, Wang and Liu (2015) report that “One of the astronauts on Apollo 15 suffered myocardial infarction after spaceflight, and another astronaut on Soyuz had to go back to Earth due to the severe cardiac arrhythmia” (p. 793). In addition, space physiology problems are further exacerbated by environmental factors such as a sense of isolation and narrow working environments (Zhang et al, 2015) as well as high concentrations of CO<sub>2</sub> and low lights levels (Buckey, 2006).

While crew members receive specialized rehabilitative treatments upon their return to Earth, the most effective interventions developed to date for use in space are the use of treadmills and bungee cords to keep crew members in place, resistance exercise devices and an ergometer (Buckey, 2006). Nevertheless, studies continue to show that even with the most aggressive

countermeasure program, crew members on space mission experience a loss of calcium that can cause orthostatic intolerance that results in accelerated heartbeat, faintness, nausea, or dizziness when they stand (Christensen, 2009). In addition, the microgravity environment of space vehicles can cause physiological changes that resemble ageing (Hargens, Bhattacharya & Schneider, 2013).

The importance of these issues has become more pronounced in recent years as space missions have gotten longer and researchers plan for a mission to Mars by the 2030s. For instance, Vakoch (2011) points out that, “An understanding of the problems and their amelioration is essential if a man desires to occupy space for extended periods of time. Even more important from a scientific perspective, it seems likely that significant advances in our basic knowledge of human interaction” (p. 9). Therefore, developing a timely and informed answer to this research question represents an important step in achieving the goal of a Mars mission and extended stays on the ISS.

**Program outcomes that will be addressed by this question:**

**Program Outcome #3:** *The student will be able across all subjects to use the fundamentals of human factors in all aspects of the aviation and aerospace industry, including unsafe acts, attitudes, errors, human behavior, and human limitations as they relate to the aviators adaption to the aviation environment to reach conclusions.*

This program outcome will be addressed using a literature review and synthesis to gain a better understanding concerning human behaviors and limitations in space. It will also address their implications for causing potentially catastrophic errors and changes in psychological attitudes as well as what interventions have been shown to be effective in mitigating them as follow.

This literature review and synthesis will address this factor by identifying what space physiology problems can result in *unsafe acts* on the part of crew members and what steps can be taken to mitigate them using various studies from physiology journals.

This part of the program outcome will be addressed by evaluating the effects of crew member *attitudes* on their physical performance and functioning during lengthy space missions using the above-listed resources.

Like the unsafe acts element, this factor will be addressed by determining how space physiology problems can cause *human errors* by crew members and how these problems can be mitigated drawing on the aforementioned resources.

This factor will be addressed by identifying what types of *human behaviors* mitigate or exacerbate space physiology problems using the above-described resources as well as scholarly texts such as Buckey (2006) and Vakoch (2011).

Finally, this issue will be addressed by identifying human physical and psychological limitations that are caused or exacerbate by space physiology problems and what steps can be used to mitigate them using the above-listed peer-reviewed and scholarly textual resources.

**Program outcome #4:** *The student will be able to develop and/or apply current aviation and industry-related research methods, including problem identification, hypothesis formulation, and interpretation of findings to present as solutions in the investigation of an aviation/aerospace-related topic.*

This program outcome will be addressed using a qualitative *research method*. The qualitative data will include studies of crew members on extended Russian Mir program missions (Buckey, 2006) as well as statistical data published by NASA concerning bone loss and kidney stone formation over time. The analysis of this data will be used to identify the key

problems, formulate a hypothesis concerning current best practices in addressing these problems during long duration space flights including the planned mission to Mars.

The ***problem*** states that there are numerous space physiological problems that are caused by the microgravity environment that astronauts have to work in, these include bone density decrease, cardiovascular deconditioning, and muscle atrophy. Aerospace medicine community is still in its infancy in finding better solutions for the problems caused by microgravity.

The ***H1*** states, can microgravity induced physiological issues to be counteracted with current methods such as resistive exercising, pharmaceuticals, and nutrition to support a manned mission to Mars.

The ***H0*** states, current methods i.e. resistive exercising, pharmaceuticals and nutrition are not counteracting microgravity induced physiological issues and thus would prove a manned Mars mission impractical. The ***interpretation of findings*** will include a summary of recent studies explaining the science behind resistive exercising, also a brief summary on pharmaceuticals that are currently being utilized and the importance of nutrition in decreasing these effects. In addition, the researcher will analyze future methods being developed and give recommendations.

**Program Outcome #9:** *The student will investigate, compare, contrast, analyze and form conclusions to current aviation, aerospace, and industry-related topics in safety systems, including systems safety, industrial safety, accident investigation and analysis, transportation security, airport safety and certification, safety program management, and aviation psychology.*

This program outcome will be addressed by investigating best practice recommendations from recent studies on space physiology in the aerospace industry, including relevant ***systems safety*** issues and what countermeasures have been used to address the physiological problems

that are caused by living and working in outer space and comparing and contrasting their efficacy to provide an analysis concerning optimal solutions to form conclusions that are relevant to current *aerospace safety* issues. A review of the relevant literature and a synthesis of the findings will be performed to investigate studies by NASA and peer-reviewed resources concerning the types of *aerospace psychology* issues that are typically experienced by astronauts and a comparison of steps that have been shown to be most effective in mitigating them to provide a timely analysis and provide the basis for formulating a relevant conclusion. The *transportation security, industrial safety, certification, safety program management, and accident investigation and analysis* aspects will not be covered by this question.



## **Final Comprehensive Exam Project**

### **Comprehensive Exam Question #1**

**Statement of the question:** “What are the effects of long duration spaceflight on crew performance and functioning, and what should be done to facilitate long-term spaceflight missions?”

### **Research and Analysis of the Question**

One of the major constraints involved in planning for long duration spaceflights is the lack of knowledge concerning the psychological and physical effects of these missions on crew performance and functioning. The research to date has been based on crew member adaptation to microgravity environments using data from extended space missions on the Russian Mir program, U.S Space Shuttle and the International Space Station, but this research has not been able to gauge the effects of high levels of cosmic ray energy on crew performance and functioning because these effects cannot be replicated on Earth (Setlow, 2003).

What is known at present is that crew performance deteriorates over time in weightless and microgravity environments and a number of physical and psychological problems can develop to the point where crews may become dysfunctional. For example, Vakoch (2011) emphasizes that “It is a mistake to try to assess and maximize performance without understanding group dynamics, the effects of isolation and confinement or the environment in general on inhabitants” (p. 59). Moreover, many of the studies to date have produced conflicting results based on the types of tests that have been used (Vakoch, 2011). Consequently, identifying relevant human behaviors and limitations in this context can provide the framework needed to reach appropriate conclusions concerning the effects of long duration spaceflight on

crew performance and functioning and what steps should be taken to mitigate these problems in the future.

### **The Effects of Long Duration Space Flight on Human Behavior**

Long duration space flights have been linked to a potential increase in the likelihood of unsafe acts by spaceship crew members. According to the Pennsylvania Department of Labor and Industry, 80% of all accidents on Earth are caused by unsafe acts, with some common examples including taking shortcuts, being overconfident, initiating a task without complete instructions, ignoring safety procedures, poor housekeeping practices, mental distractions from tasks, and the failure to pre-plan the work (Unsafe Acts, 2012). It is reasonable to suggest that not only can all of these unsafe acts easily occur on long duration space flights, but the potential for their occurrence is likely far greater in microgravity, confined and isolated space habitats than in working environments on Earth (Zhang et al., 2015).

The potential for crew members to commit unintentional and perhaps even intentional unsafe acts on long duration space missions are significant due to the known effects of length space flight on the human body and mind as well as the possible effects of lengthy confinement in an isolated working and living environment. As Setlow (2003) emphasizes, "Space is an unforgiving environment that does not tolerate human errors or technical failure. For humans leaving Earth's orbit for extended periods, there are even more dangers" (p. 1013). As noted above, these dangers include the microgravity environment of space and high levels of ionizing cosmic ray energy, both of which can have deleterious and additive effects on crew member health and performance during long duration space missions that can result in various but yet undetermined unsafe acts (Setlow, 2003). To give a realistic illustration, current astronauts returning from 6 month missions to the International Space Station going from a 0g to 1g

environment are being diagnosed with Orthostatic Intolerance. Orthostatic Intolerance is the inability to maintain a stable blood pressure which leads to near-syncopal episodes and lightheadedness which is a clear indication of a decrease in blood flow to the brain. Astronauts that would be traveling on long duration spaceflights such as those to Mars would be traveling for at least 6 months to a year in possible hibernation pods indicating limited mobility in microgravity. This implication certainly confirms that even if Mars is 1/3 the gravity of Earth, it would still take a considerable amount of time for the astronaut to readapt after landing on the Martian planet.

The full range of psychological, physiological, physical and psychosocial stressors discussed further below under human limitations can accentuate any naturally occurring interpersonal differences between crew members (Morphew, 75) and their attitudes towards each other and their mission can be expected to suffer as a result. In this regard, Manzey (2004) emphasizes that “The biggest psychological challenges astronauts have to cope with during prolonged space missions are related to the numerous habitability, psychological and interpersonal stressors they are exposed to” (p. 782). As discussed further with respect to human behavior and limitations, these stressors include Spartan type accommodations, limited living and working areas, the different workload levels assigned to each crew member, sustained enforced contact with other crew members, a general paucity of privacy, and separation from crew members’ normal social network (Manzey, 2004).

### **The Effects of Long Duration Space Flights on Crew Performance and Functioning**

While it is difficult to predict the precise effects of these different stressors on crew member performance and functioning during long duration space flights, current research indicates that the sustained enforced contact with other crew members and the accentuation of

any naturally occurring interpersonal conflicts may be among the most important, due in part perhaps to the other stressors such as a basic lack of privacy, the separation of their normal social network and the limited working and living areas that are available in which to obtain some much-needed “personal space in outer space.” In this regard, Manzey (2004) pointed out that, “problems arising from interpersonal frictions and conflicts have repeatedly been reported from confined and isolated crews and have also been observed during orbital space missions” (p. 782).

A study by Shappell and Wiegmann (2000) found that many of the same types of errors that are characteristic of aviation are also applicable to long-duration space flights, including:

1. *Skills-based errors* (these types of errors include the failure to prioritize attention, the omission of checklist items, over-control, omitted steps in a procedure, and a breakdown in visual scan);
2. *Decision errors* (these types of errors include the use of improper procedures, the exceeding of individual ability, poor decision-making, inappropriate maneuvers, and misdiagnosed or wrong response to emergencies); and,
3. *Perceptual errors* (these types of errors include misjudged distance/speed, spatial disorientation and visual illusions).

An important but understudied problem that could adversely affect crew performance and function on long duration space missions that are inextricably interrelated with human behavior is the potential for so-called “groupthink” to develop (Manzey, 2004). According to Manzey,

“This phenomenon has been observed to develop in highly autonomous and cohesive groups working under stress, and is characterized by different symptoms which might seriously affect crew performance and interactions with ground, e.g. delusions of invulnerability (i.e. group members show an unreal confidence in their own competence), high group pressure towards uniformity (i.e. crew members show reluctance to express concerns or disagreement about certain decisions or ways of action in order to keep harmony), and stereotyped views of people outside the own group” (p. 785).

A final and also seriously understudied issue concerns human behavior and sex on long duration space missions. Although there have been no formal reports of these behaviors by crew members on the Russian Soyuz or Mir, Space Shuttle or ISS missions, this potential assumes far greater relevance on longer duration space flights (Oberhaus, 2013). Despite more than a half century of space missions to date, NASA and other space agencies have not seriously studied this aspect of space travel because most missions have not been of sufficient duration. Prolonged missions aboard the ISS and the envisioned Mars mission, though, will inevitably result in this aspect of human behavior to become an important consideration (Oberhaus, 2013).

A study by Morphew (2001, pp. 75-76) identified a number of stressors that will be involved in long duration space missions that will be affected by human limitations, including psychological, physiological, physical and psychosocial stressors as set forth in Table 1 below.

**Table 1:** *Stressors of long duration space flight*

Stressor Category	Description
<b>Physiological and Physical Stressors</b>	<ul style="list-style-type: none"> <li>• Radiation (Cosmic/Deep Space and Solar)</li> </ul>
	<ul style="list-style-type: none"> <li>• Absence of natural time parameters</li> </ul>
	<ul style="list-style-type: none"> <li>• Altered circadian rhythms</li> </ul>
	<ul style="list-style-type: none"> <li>• Decreased exposure to sunlight</li> </ul>
	<ul style="list-style-type: none"> <li>• Physiological and physical adaptation to microgravity (also a psychological stressor)</li> </ul>
	<ul style="list-style-type: none"> <li>• Sensory and perceptual deprivation of varied and natural sources</li> </ul>
	<ul style="list-style-type: none"> <li>• Noise and vibration exposure from spacecraft systems (Chronic)</li> </ul>
	<ul style="list-style-type: none"> <li>• Light and illumination</li> </ul>
	<ul style="list-style-type: none"> <li>• Space Adaptation Sickness (SAS)</li> </ul>
	<ul style="list-style-type: none"> <li>• Sleep Disturbance</li> </ul>

Stressor Category	Description
<b>Psychological Stressors</b>	<ul style="list-style-type: none"> <li>• Isolation and confinement</li> </ul>
	<ul style="list-style-type: none"> <li>• Mission danger and risk associated with: equipment failure/ malfunction/damage, limited equipment, facilities, and supplies, limited possibility for abort/rescue</li> </ul>
	<ul style="list-style-type: none"> <li>• High-risk conditions and potential for loss of life</li> </ul>
	<ul style="list-style-type: none"> <li>• System complexity and mission complexity</li> </ul>
	<ul style="list-style-type: none"> <li>• Hostile external environment</li> </ul>
	<ul style="list-style-type: none"> <li>• Limited exchange of information and communications with external environment</li> </ul>
	<ul style="list-style-type: none"> <li>• Limited means of expressing general tension to crew and mission control</li> </ul>
	<ul style="list-style-type: none"> <li>• Alterations in sensory stimuli</li> </ul>
	<ul style="list-style-type: none"> <li>• Adaptation to artificially-engineered environment</li> </ul>
	<ul style="list-style-type: none"> <li>• Limited habitability</li> </ul>
	<ul style="list-style-type: none"> <li>• Food (some restrictions/limitations in variety, aesthetic appeal)</li> </ul>
	<ul style="list-style-type: none"> <li>• Periods of too high or too low workload</li> </ul>
	<ul style="list-style-type: none"> <li>• Physiological and physical adaptation to microgravity</li> </ul>

Stressor Category	Description
<p><b>Psychosocial and Team-Performance Stressors</b></p>	<ul style="list-style-type: none"> <li>Limited means of hygiene and Disruptions of sleep patterns</li> </ul>
	<ul style="list-style-type: none"> <li>High-team coordination demands</li> </ul>
	<ul style="list-style-type: none"> <li>Presence of naturally occurring interpersonal tension between crewmembers</li> </ul>
	<ul style="list-style-type: none"> <li>High proximity of human-human interactions</li> </ul>
	<ul style="list-style-type: none"> <li>Lack of privacy from fellow crewmembers and mission control</li> </ul>
	<ul style="list-style-type: none"> <li>Crew factors (gender, size, personality, multiculturality, heterogeneity)</li> </ul>
	<ul style="list-style-type: none"> <li>The “Host-Guest” phenomenon (readjustment with crew changeovers)</li> </ul>
	<ul style="list-style-type: none"> <li>Isolation from regular social support systems</li> </ul>
	<ul style="list-style-type: none"> <li>Social conflict</li> </ul>
	<ul style="list-style-type: none"> <li>Disruption to family life</li> </ul>
<ul style="list-style-type: none"> <li>Enforced interpersonal contact</li> </ul>	



Although NASA is currently conducting field tests concerning the effects of long duration spaceflight on humans and has collected statistical data concerning these effects with 18 astronauts and cosmonauts beginning with the 34S mission and ending with the 41S mission, this data has not yet been released (Reschke & Kozlovskaya, 2017). Some of the known adverse effects of long duration space flight on crew performance and functioning, though, include those set forth in Table 2 below.

**Table 2:** *Effects of long duration spaceflight on crew performance and functioning*

Primary	Secondary
<b>Exhaustion and Asthenia</b>	<ul style="list-style-type: none"> <li>• Fatigue, feeling of tiredness</li> <li>• Emotional Instability</li> <li>• Sleeplessness</li> <li>• Sharpening of personality</li> <li>• Incapacity for work</li> <li>• Disruption of psychophysiological reaction</li> <li>• Psychosomatic dysfunction</li> </ul>
<b>Euphoria</b>	
<b>Depression</b>	
<b>Neurosis</b>	
<b>Accentuation of negative</b>	
<b>Personality traits</b>	
<b>Cognitive effects</b>	<ul style="list-style-type: none"> <li>• Psychomotor performance</li> <li>• Dual-task performance</li> <li>• Tracking performance</li> <li>• Fine manual control</li> <li>• Sleep-decrement induced cognitive factors (alertness, vigilance, response time, ability to focus).</li> </ul>

*Source: (Morphew, 2001)*

Besides the need for additional research concerning appropriate countermeasures for these stressors and their physical and psychological effects (Zhu et al., 2015), ameliorating these foregoing issues will also require a multifaceted approach that includes taking individual crew member preferences where possible (Manzey, 2004). At present, some of the in-flight support countermeasures that are used for lengthy space missions will not be available or will be limited by longer duration space travel such as a mission to Mars while others will need to be modified to take into account the longer distances that are involved and the constraints this introduces for two-way communications with Earth-based crew and individual social networks.

There are two basic types of countermeasures that can be used to address the physical and psychological problems that may be caused by long duration space missions: (1) ongoing monitoring of the mental and physical status of crew members by Earth-based clinicians and technicians to identify any issues or problems that require interventions, and (2) general and personalized support measures. The efficacy of both types of these countermeasures, of course, will become increasingly attenuated as distances between Earth and a space vehicle increase such as on a mission to Mars since two-way communication times will increase, thereby causing delays in crew member monitoring as well as in the ability to provide personalized support in the form of written communications from family members and friends which will become increasingly difficult. For instance, Manzey (2004) emphasizes that the provision of personalized countermeasures “involves several support measures that are provided in order to prevent feelings of monotony, boredom, and social isolation. Important elements of these countermeasures are based on two-way audio/video transmissions between space and ground” (p. 786).

Besides personal communications with their Earth-bound social networks and private family conferences through Internet phone service, these increased distances will also adversely

affect the ability of ground-based personnel to provide the real-time counseling and support that are currently used for crew members. In this regard, Manzey (2004) adds that,

“One of the most important psychological monitoring and support tool for ISS crews consists of ‘private psychological conferences,’ i.e. audio/video conferences between crewmembers and their psychological support station on ground which are conducted on a regular basis and which also might be used for providing psychological counseling and guidance if needed” (p. 786).

In addition, the ability of Earth-based personnel to evaluate indicators of stress such as voice pattern analyses which have been used by Russian support personnel will become increasingly difficult and therefore less effective (Manzey, 2004). Likewise, “CARE” packages containing letters from home, favorite food items, small gifts, and new videos or music recordings that have been delivered to crew members by re-supply missions will either be unviable or will require a far longer timeframe in the future on a mission to Mars (Manzey, 2004). Therefore, current countermeasures that are being used to address the problems that are associated with long duration space flight must be reevaluated in view of these constraints (Manzey, 2004).

Finally, two of the more interesting findings to emerge from the Manzey (2004) study were that: (1) “It is likely that e-mail will become the most important communication tool during missions to Mars” and (2) “Studies will be needed that address the advantages and disadvantages of e-mail communication as the sole tool for maintaining social contacts between crew members and ground, as well as a tool to provide remote psychological counseling and guidance” (p. 786).

### **Conclusion**

The current research is consistent in showing that long duration space travel can have a wide array of adverse effects on crew members extending across the full range of physical and psychological effects. There is a solution to the cephalad fluid shift issue caused by microgravity that continues to cause a myriad of physiological problems to include muscle atrophy, intracranial pressure, cardiovascular arrhythmias, and orthostatic intolerance issues experienced after landing. The solution is the creation of an artificial gravity environment otherwise known as simulated gravity aboard the spaceship. It can be done by rotating the space habitat thus centrifugal force pulls the inhabitants on the outside and if the rate of rotation and the radius of the object being rotation is adjusted, then it could equal that of the 0g hence making it 1g. Although this solution is only seen in science fiction movies, it works but it still remains in theory due to the extent of the endeavor one would have to take to accomplish such a feat. It is without reservation that the research indicates that more studies are necessary, it is clear that the longer humans are in space, the more likely it will be for them to experience these adverse effects and to make errors in judgment as a result. It remains quite clear that without countermeasures, these issues researched would negatively affect spaceship crew health and their ability to execute important mission functions aboard the spacecraft on a long duration mission or after landing on another planetary body. With respect, test missions in underwater habitats or Antarctic expeditions continue to provide some analogous comparison of these effects with respect to a sense of isolation and confinement. There are no comparable parallels to long duration space travel that can be used to predict how these effects will manifest themselves and how astronauts would react millions of miles from Earth.

**Comprehensive Exam Question #2**

**Statement of the question:** “How should current human-machine design interfaces be enhanced to make manual rendezvous and docking in space easier to perform?”

**Research and Analysis of the Question**

Given the rapid increase in the complexity of space vehicles, it is reasonable to suggest that current human-machine design interfaces may lack the ease of use considerations required for manual rendezvous and docking in space. At present, manual rendezvous and docking missions typically require the use of different types of navigation sensors that may eventually allow for autonomous rendezvous missions in the future (Dennehy, 2016). For instance, Dennehy (2016) reports that “Autonomous rendezvous could also lead to lower operational costs. More autonomy may eventually reduce the workload for on-ground crews or the pilots and crews in the spacecraft itself” (p. 3). Currently, though, manual rendezvous and docking maneuvers in space remain a challenging enterprise for space crewmembers (Du, Zhang, Tian, Huang, Wu & Zhang, 2015), creating a vital need for enhanced human-machine interfaces.

In high risks environments, in this instance, microgravity; tasks so minute such as docking that might seem so minute on Earth if not executed with the utmost accuracy could lead to a total and complete loss of life and spacecraft. This is the reason why it is very important to study various methods and innovations to enhance manual rendezvous and docking in space. It has been noted by NASA Human Health and Performance Program that not enough experimentation exhibiting the effects of disorientation and how this can affect spatial skills while performing manual rendezvous and docking operations. In the day and age of SpaceX and Blue Origin, where we are looking at the Martian planet as the new frontier, it remains imperative that factors such as this that could increase the likelihood of mission failure are evaluated. Tools and cognitive performance monitors have to be put in place to counteract a

possible skill based, decision and perceptual based error of this kind if it is to occur while aboard a spacecraft (Wang et al., 2014).

To date, the majority of research into manual docking rendezvous missions has focused on the effects of spatial abilities among inexperienced crew members rather than experts (Du et al., 2015). However, previous studies have suggested that it is not possible or extremely difficult to compensate for deficiencies in the types of spatial abilities that are required for manual docking maneuvers in space, Du and his colleagues (2015) determined through simulation testing that experts consistently performed better than their inexperienced counterparts, highlighting the need for more experience through ground-based training opportunities prior to deployment on space mission (Du et al., 2015).

Like many of the other issues examined in this study, there remains a need for additional studies concerning the multimodal aspects of manual rendezvous and docking missions (Wang et al., 2014). Likewise, Du et al. (2015) emphasize the need for additional research in this area. The research to date, however, indicates that the specific cognitive abilities such as spatial abilities that are required for these maneuvers can be improved through training (Wang et al., 2014). The specific cognitive abilities that contribute to successful docking maneuvers, though, are also an issue under investigation and these are discussed further in the technological area below.

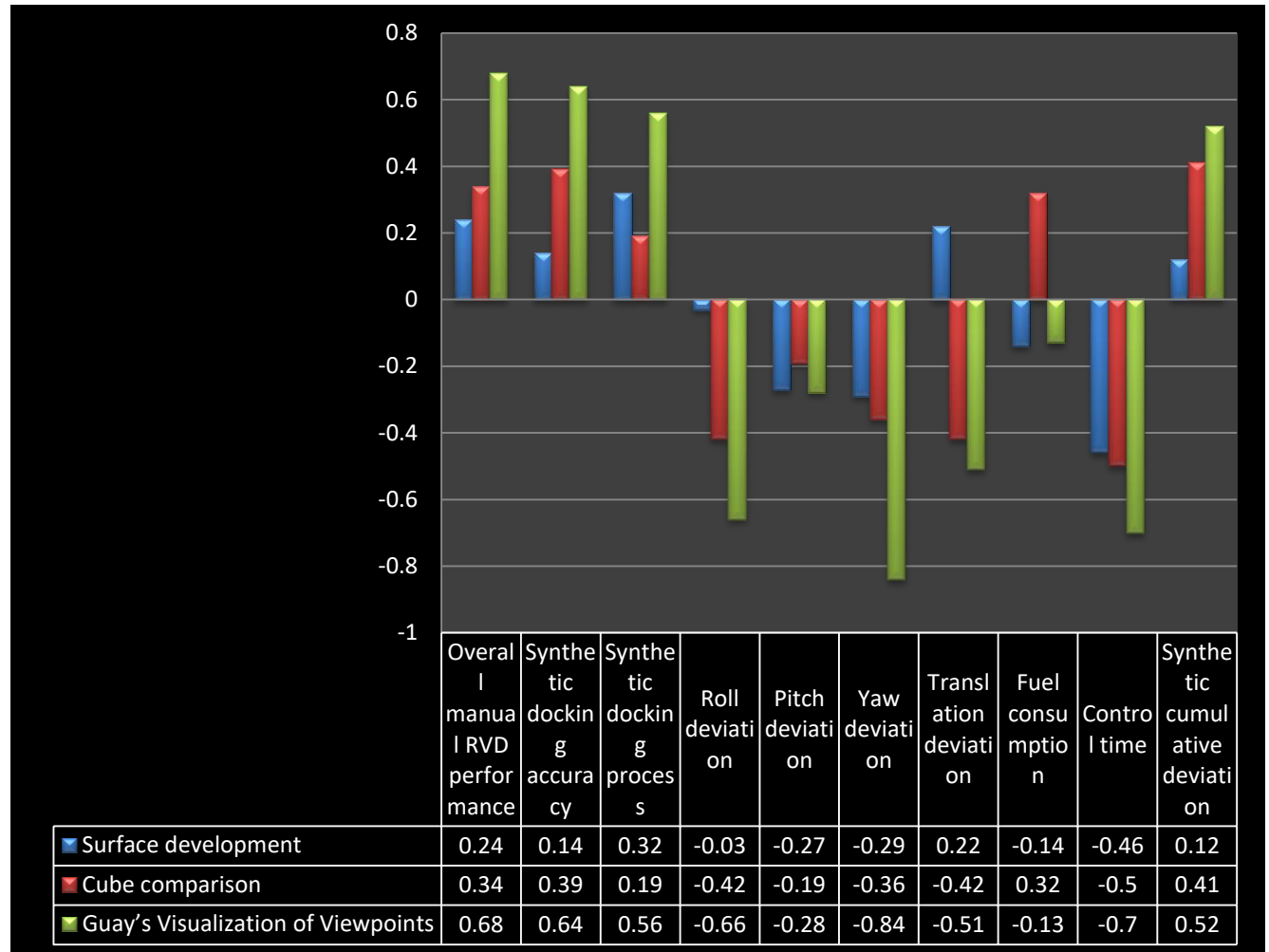
The technological aspects of manual rendezvous and docking maneuvers are addressed by drawing on the results of simulated manual rendezvous and docking (manual RVD) studies designed and developed by industry experts. A linear regression of the results of these

studies at the China Astronaut Research and Training Center by Wang et al. (2014). This data is used to identify relationships between spatial ability and manual RVD performance data as set forth in Table 3 and depicted graphically in Figure 1, 2, and 3 below.

**Table 3:** *Correlations coefficients between the spatial ability test data and the manual RVD performance data*

	Surface Development	Cube Comparison	Guay’s Visualization of Viewpoints
Overall manual RVD performance	0.24	0.34	0.68
Synthetic docking accuracy	0.14	0.39	0.64
Synthetic docking process	0.32	0.19	0.56
Roll deviation	-0.03	-0.42	-0.66
Pitch deviation	-0.27	-0.19	-0.28
Yaw deviation	-0.29	-0.36	-0.84
Translation deviation	0.22	-0.42	-0.51
Fuel consumption	-0.14	0.32	-0.13
Control time	-0.46	-0.50	-0.70
Synthetic cumulative deviation	0.12	0.41	0.52

*Source: (Wang et al., 2014)*

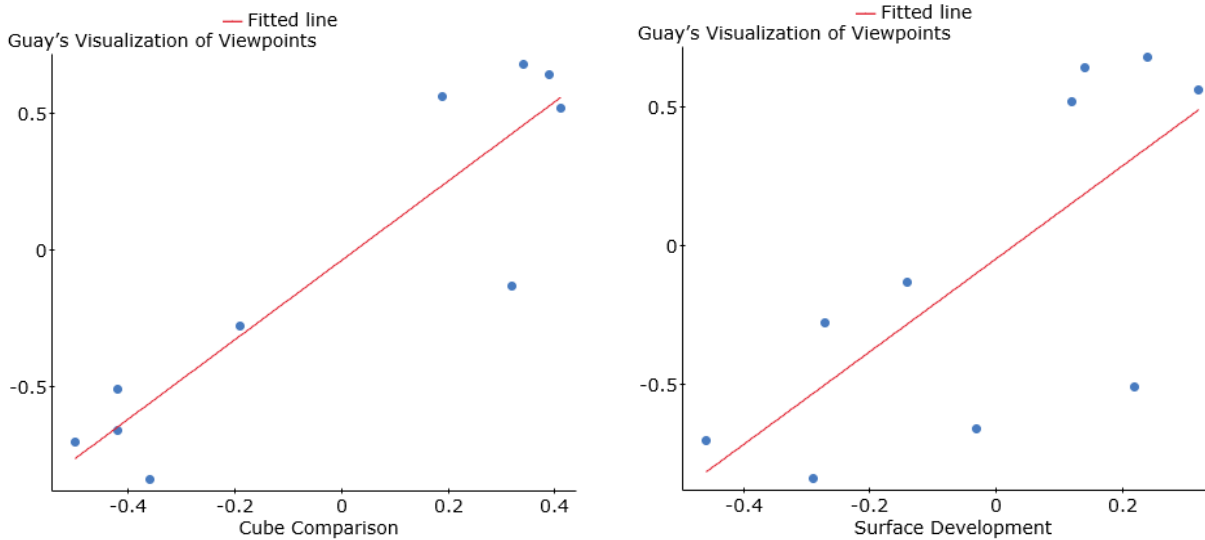


**Fig. 1.** Correlations coefficients between the spatial ability test data and the manual RVD performance data (Source: Compiled from Wang et al., 2014)

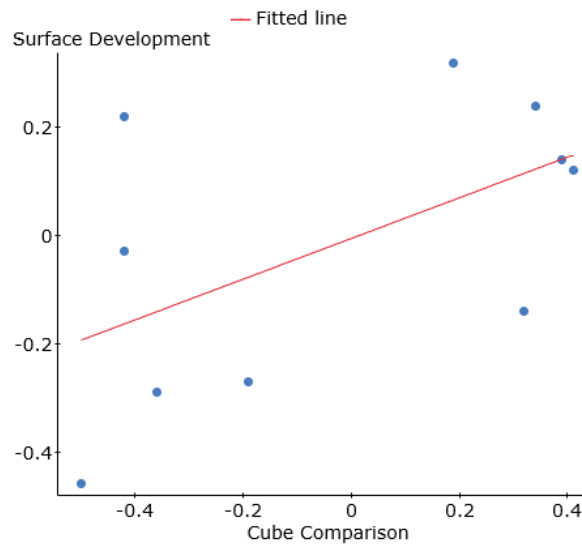
As shown in Table 3 and depicted in Figure 1 above, the Pearson correlation coefficients between the spatial ability measures and the manual RVD performance indices used four indices of the manual RVD performance (i.e., overall manual RVD performance, synthetic docking accuracy, synthetic docking process, and cumulative deviation) and six manual RVD performance indices (i.e., roll deviation, pitch deviation, yaw deviation, translation deviation, control time, and fuel consumption); for each index, lower values indicate better manual RVD performance (Wang et al., 2014).



The results of the linear regression analysis showed that the model was only stable with the test scores generated by Guay’s Visualization of Viewpoints predictive variable (Fig. 2).



**Fig. 2.** Linear Regression Surface Development & Cube Comparison using Guay’s Visualization of Viewpoints (Stable)



**Fig. 3.** Linear Regression Surface Development & Cube Comparison (Unstable)

In this regard, Wang et al. (2014) conclude that, “The test score of Guay’s Visualization of Viewpoints test accounts for 42.3% of the variance in overall manual RVD performance data

(Table 3), 36.8% of the variance in synthetic docking accuracy data, and 26.2% of the variance in synthetic docking process data” (p. 367). These findings suggest that current human-machine design interfaces should be enhanced with respect to docking accuracy and the docking process to improve overall manual RVD operations (Wang et al., 2014).

**Social Issues Associated with Human-Machine Interface Design**

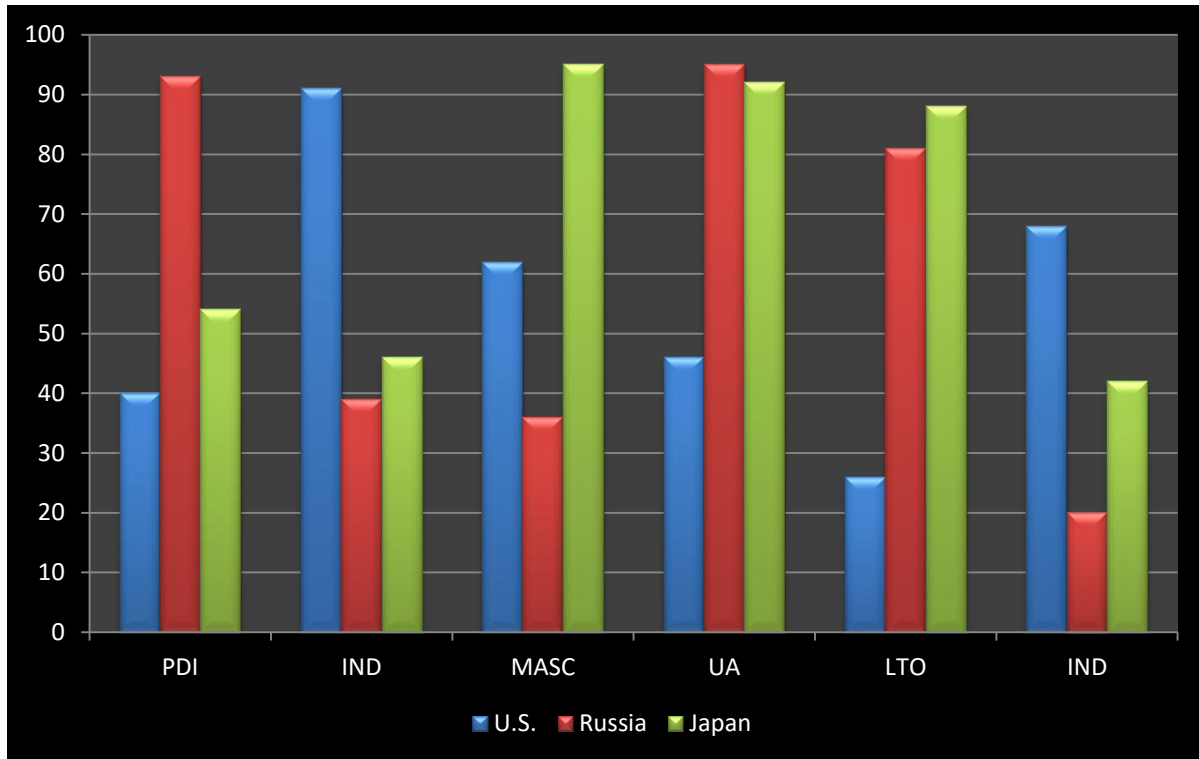
The need to take social issues into account when designing human-machine interfaces for the ISS is obvious. For instance, according to Betts, Del Mundo, McIntosh and Niehaus (2002), “The International Space Station (ISS) is a collaborative engineering and scientific endeavor among sixteen nations. Its design and ongoing assembly and operation are complex undertakings” (p. 500). To date, crew members and tourists from sixteen different nations have stayed on the ISS for varying lengths of time as follows (crew members typically stay longer than tourists), with the United States, Russia, Canada and Japan have sent the most crew members and tourists (Rundle, 2013). As shown in Table 4 and depicted graphically in Figure 4 below, there are some significant cross-cultural differences between these nations (Canada is subsumed with the U.S. data since these two countries are virtually mirror images with respect to Hofstede’s cultural dimensions):

**Table 4:** Hofstede’s cultural dimension scores for the U.S., Russia and Japan

Country	PDI	IND	MASC	UA	LTO	INDG
U.S.	40	91	62	46	26	68
Russia	93	39	36	95	81	20
Japan	54	46	95	92	88	42

Legend:

- PDI = Power distance                      IND = Individualism
- MASC = Masculinity                      UA = Uncertainty Avoidance
- LTO = Long-term orientation            INDG = Indulgence



**Fig. 4.** Hofstede's cultural dimension scores for the U.S., Russia and Japan  
(Source: Compiled from Hofstede, 2017)

As can be readily discerned from the stark cross-cultural differences between the U.S., Russia and Japan depicted in Figure 4 above, crew members from different countries may have significantly different social views about the types of human-machine interfaces they prefer, and optimizing these systems may require the use of native languages and built-in alternative approaches to improve their ease of use. Let's take, for example, American astronauts currently have to learn the Russian Soyuz TMA spacecraft systems and design interfaces. From a cultural dimension perspective in regards to Figure 4, this means having to learn a new language (Russian), there is also a high probability of spacecraft systems being in different places due to the culture of the hosting country and differentiations in mission pertinent hot keys that are utilized to either perform maneuvers or initiate emergency protocols aboard the spacecraft. As one can imagine in this realistic scenario, this would place the individual on a shallow learning curve.

According to Wang et al. (2014), the relationship between the different types of cognitive demands that are required for manual rendezvous and docking maneuvers in space require the identification of the primary cognitive abilities that affect task performance. This identification serves to determine the types of ground-based training opportunities most appropriate as well as how human-machine interfaces should be enhanced to facilitate task performance (Wang et al., 2014).

In an effort to ensure that all stakeholders were provided with a voice in the design of the ISS, a Space Station Panel (SSP) was created and tasked with the following mandates:

- Review and evaluation of projected goals for ISS research;
- Development of processes by which NASA will define the roadmap and its implementation strategies, including the criteria for prioritizing overall mission objectives as well as specific programmatic elements;
- Review of currently available plans for completion of the ISS and restoration of a full crew size;
- Identification of research and technology testing for which the ISS may provide a uniquely suitable platform and consideration of the ISS-based facilities essential for such research and testing; and,
- Identification of potential gaps in projected programs and facilities for utilization of the ISS.

In addition, the SSP was provided with the results of a series of comprehensive studies concerning the design elements that would be used on the ISS. The SSP determined that there remained a need to prioritize what design elements should take precedence and that the criteria and processes that were in place were poorly defined. In response, the SSP recommended that an integrated plan should be developed for future design efforts that included all stakeholders as well as members of the global scientific and technical communities to ensure that best practices are applied to the ISS in the future (Review of NASA plans for the International Space Station, 2006). The SSP is the body that was created for implementing ergonomics and methodology of equipment that might be added to the International Space Station with input from each country

involved, it is ill-timed that this panel's purpose has been realized as the ISS looms decommissioning.

### **Other Human Factors Involved in Manual Rendezvous and Docking Maneuvers**

Reference is made to the common unsafe acts previously described herein (i.e., taking shortcuts, being overconfident, initiating a task without complete instructions, ignoring safety procedures, poor housekeeping practices, mental distractions from tasks, and the failure to pre-plan the work). Although these types of unsafe acts have serious consequences on Earth, the effects on a space mission are catastrophic (Roesler, 2009). To help mitigate the potential for unsafe acts on space missions, Wang et al. (2014) recommended that tasks that place strong demands on spatial orientation abilities should not be scheduled during periods of spatial disorientation, suggesting that human-machine design interfaces should compensate for diminished spatial abilities during manual rendezvous and docking maneuvers. In addition, Du et al. (2015) recommend human-machine interfaces provide improved three-dimensional representation of the target spacecraft in order to facilitate precision alignment with the chasing spacecraft.

Schlacht and Birke (2011) study is centered around the need to consider the type of visual interface that is used in space habitats to improve the quality of the living and working environments as well as the attitudes of crew members concerning their habitat. In addition, Petit et al. (2011) cite the need for enhanced three-dimensional representations of the docking maneuvers to facilitate rendezvous missions, a feature that can be reasonably expected to improve crew member attitudes about the task. Finally, interviews with past ISS crew members also emphasized the need for improved interfaces, especially with respect to the ease with which different functions were able to be located in equipment panels with one American astronaut

stating, “Locatability is so bad it almost looks like you had to go out of your way to design it that way” (Kitmacher, 2002, p. 4).

One of the consistent themes that run through the above-mentioned studies is the hostile and constrained environment in which crew members live and work. With a wide array of psychological and physical stressors diminished crew members’ ability to perform at optimal levels across the entire spectrum of tasks that are required for manual rendezvous docking maneuvers. Besides the diminished spatial abilities that are critical to these missions, other cognitive and physical faculties are also adversely affected in varying and unpredictable ways, making the propensity for error-making high and the need for appropriate enhanced interfaces to compensate all the more important.

Despite assertions from previous ISS crew members that they are all professionals in their fields and are fully dedicated to achieving their respective missions (Oberhaus, 2015), their reactions to poor design elements can result in purely human behavioral responses. For instance, one Skylab commander, Gerry Carr, reported during his mission, “I get one local vertical embedded in my mind, and I whistle down the tunnel and into the command module and zing, all of a sudden it’s upside down” (Kitmacher, 2002, p. 4). Likewise, another crew member reported even being, “upset” at the design, an issue which could easily accentuate any existing psychological problems: “Well, all I gotta say is, if you are looking for a very good example of how not to design and arrange a compartment, the docking adapter is the best example. Every time I think about how stupid the layout is in there I get all upset” (Kitmacher, 2002, p. 4). Clearly, there are numerous opportunities to facilitate manual rendezvous and docking missions by taking these human factors into account.

A study by Kitmacher (2002) provided several recommendations from previous crew members concerning ways to improve human-machine interfaces that relate to human limitations

in space, including most especially the need to improve locability. It was also recommended that a “Consistent local vertical should be maintained within any compartment with a contiguous field of view. The lower decks of the workshop wasted a lot of space. The docking compartment is more efficient, but even he had difficulty finding things when he went in there” (Kitchmacher, 2002, p. 4).

Likewise, Palamidese, (1999) also calls for additional consideration of human factors when designing interfaces for space habitats and vehicles: “Crew performance can be better supported by the careful management of mission protocols, workload, fatigue, and cognitive demands, in addition to the implementation of human factors and habitability in the design of spacecraft systems/interfaces” (p. 59).

### **Conclusion**

The current research shows that current human-machine interfaces need to be enhanced to make manual rendezvous and docking in space easier to perform by taking the cognitive and spatial human factor limitations of crew members into account during the design phase. In addition, while fully autonomous docking solutions are under development, there remains a profound need for crew members to be able to readily and easily identify the location of mission-specific equipment and tools which are a recurrent theme emerging from the current research. As mentioned previously, the importance of enhancement for existing human-machine interfaces cannot be disregarded especially since we are on the verge of committing to a long duration interplanetary mission to Mars. From a human factors perspective, taking into account human behaviors, cross-cultural differences and human limitations; designers will not only be paving the way for design innovations in this arena. Nevertheless they will also be paving a new path for the research and development in autonomous modes for future manual rendezvous and docking missions to other interplanetary bodies in the universe.

### **Comprehensive Exam Question #3**

**Statement of the question:** “How can emerging virtual modeling technology help solve ergonomic design problems of the International Space Station?”

#### **Research and Analysis of the Question**

Despite having an interior approximately the size of two jumbo jets, every square inch of usable space on the International Space Station (ISS) is devoted to specific equipment and functions, many of which were designed more than 3 decades ago. Missions on the ISS typically last about 6 months, and the comfort of crew members during these missions represents a vital part of helping them remain effective (International Space Station, 2017). In this regard, Schlacht and Birke (2011) report that “Today, well-being, comfort and human factors are becoming important in space missions. The International Space Station was designed mainly according to the logic of short space missions (SDM) (less than 2 weeks” (p. 498). In sum, the potential value of virtual modeling technology for ergonomic design in space applications is enormous (Palamidese, 1999). Virtual modeling technology now provides researchers with the ability to replicate the three-dimensional environment in which crew members live and work in space, an attribute that is especially useful since astronauts operate in their entire environment without regard to an “up or down” orientation (Schlacht & Birke, 2011).

#### **Current Ergonomic Issues on the International Space Station**

While the environment aboard the ISS provides crew members with a number of advantages, there are some design issues in place that may become detrimental to crew member performance. In this regard, Newman (2000) emphasizes that “Human presence on space missions offers many advantages to ensure mission success: flexibility and dexterous manipulation, human visual interpretation and cognitive ability, and real-time approaches to problems. However, there are factors that may degrade human performance” (p. 35). Factors



that have been shown to adversely affect human performance in space include the encumbering effects of pressure suits, insufficient working areas, pre-breathing requirements, and suboptimal tool or task design (Newman, 2000). Therefore, there are several opportunities for solving the ergonomic design problems of the ISS using virtual modeling technology. It is without question that the ability to predict an astronaut's limitations is vital to mission completion or whether certain tasks are a reasonable request and that is what virtual modeling can ascertain in this day and age. The technology is available and is programmable to represent human interaction with complex systems in lieu of achieving human-out-of-the-loop (HOOTL) computational simulation. HOOTL is a computer modeling process that is utilized to simulate a human how he or she would interact within a computer-generated representation of their operating environment. This not only replaces the current human-in-the-loop (HITL) systems like sending astronauts unnecessarily to report their interaction within the habitat and environment which costs roughly \$70 million, HOOTL would be a method to remain cost effective. Nevertheless, still collecting a great amount of data utilizing virtual modeling whereas simulating known human factors that individuals in the habitat have or might experience. HOOTL computer based simulations require no subjects, experiments and testing time is only limited by the processing power of a computer (Gore & Corker, 2001). This virtual modeling technology can be utilized for the premature stages of development for Mars living habitats or new space station modules.

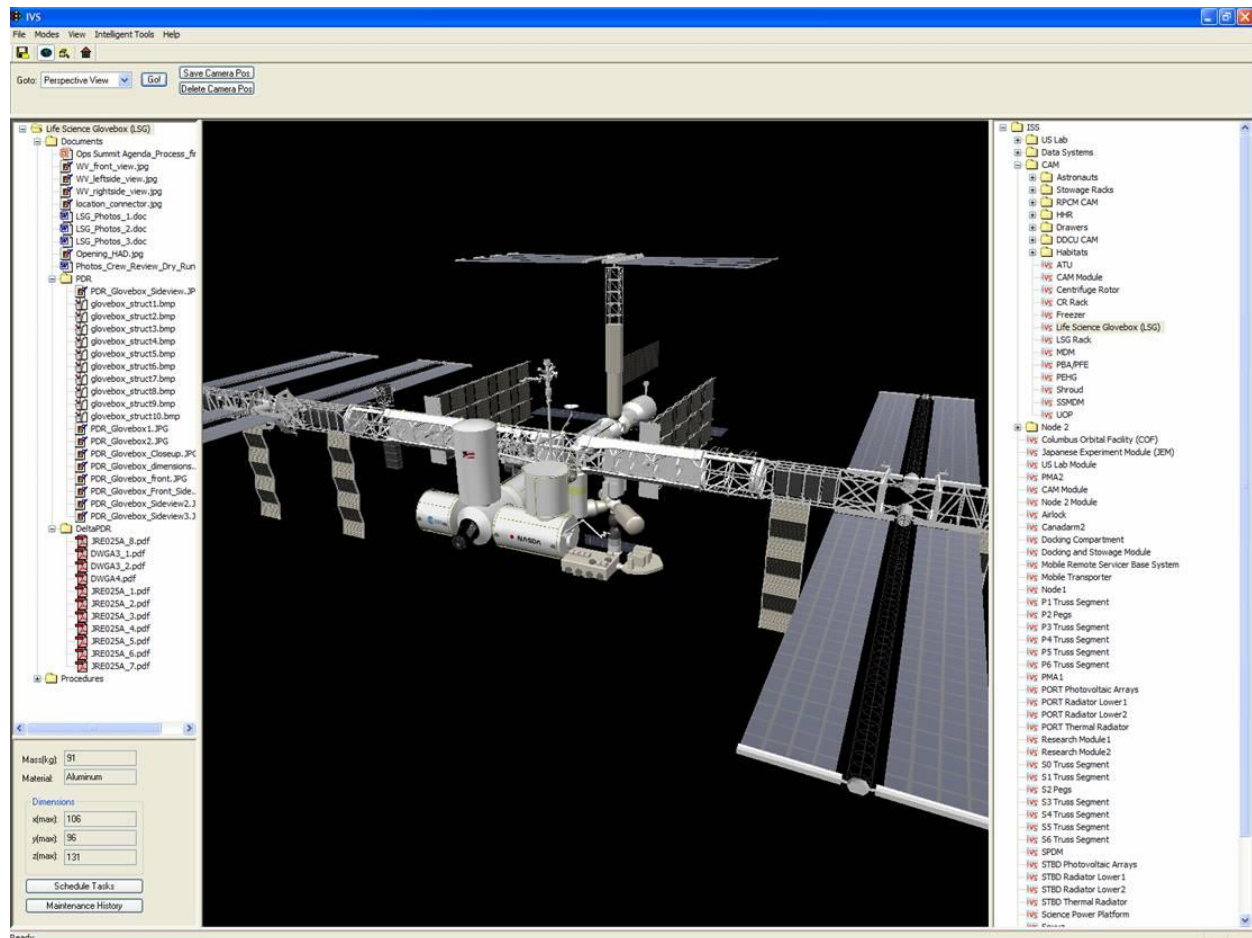
Orientation is made to the types of unsafe acts that are commonplace in industrial settings described above such as taking shortcuts, being overconfident, initiating a task without complete instructions, ignoring safety procedures, poor housekeeping practices, mental distractions from tasks, and the failure to pre-plan the work (Unsafe Acts, 2012). These types of unsafe acts are not only unpredictable, they are notoriously difficult to design against; however, it is conceivable that enhanced ergonomic design of interfaces and working environments could serve to

encourage safer practices by crew members during long term space missions. Given the outright hostility expressed by past crew members of Skylab to the less-than-optimal designs used in that habitat (Hitt & Garriott, 2008). As was previously stated, microgravity environment and space crew confinement on a space station habitat adversely influences individuals aboard both psychologically and physiologically to include bone loss, muscle atrophy, and various other health issues (Hitt & Garriott, 2008). These ramifications often lead to poor crew performance and could lead to task failure. However, real-time virtual simulation modeling that utilizes anthropometric data, astronaut behavioral traits, and 3-D geometric modeling of the human body and its response to the changing microgravity environment is the future in regards to human factors and future habitat design (Sierhuis et al., 2006). As we know, typical tasks on Earth such as unlocking a hatch can be easily accomplished but in space, it remains the complete opposite not only due to cephalad fluid shift to the individuals' upper extremities but the overall weightlessness environment (Sierhuis et al., 2006). Through the years of spaceflight, various astronaut health data has been collected and now through these simulations can be utilized in a computer simulated environment, so we can further increase our understanding of the space environment while finding countermeasures without risking human lives in the process.

### **The Effects of Poor Ergonomic Design on Crew Member Performance and Functioning**

According to Schlacht and Birke, the utilitarian nature of space habitats such as the ISS may adversely affect crew members' comfort and performance, and these issues can be reasonably expected to have a major impact on their attitudes concerning their ease of use. For instance, these researchers point out that, "In the ISS, the interior is optimized and conceived as a working interface. Racks and space furniture have an interface composed of cables, instruments, experiment equipment and storage compartments" (p. 497). An early study by Gellerman (1994)

concluded that from an ergonomic perspective, “Basically, the ultimate comfort of the user is key” (p. 15). Likewise, another early study by Vidov and Alexander (1992) noted that virtual modeling technology was already being used to identify optimal ergonomic design elements but these initial efforts were not specifically directed at space habitat design. More recently, however, NASA has been using an Intelligent Virtual Station application to improve design elements on the ISS (a typical screen capture of this application is provided in Figure 5 below).



**Fig 5.** Screen capture of Intelligent Virtual Station application obtained via NASA

This virtual modeling technology provides enhanced locability for digital information concerning tools, equipment and experiments on the ISS and includes an ergonomically designed easy-to-use interface. This interface has proven its popularity among crew trainees by providing them with the opportunity to visualize the steps that are involved in a given experiment or that

are required for component repair or replacement on the ISS (Betts et al., 2002). Moreover, training can take place in any country for months or even years prior to a mission and crew trainees are able to remain expert with the system by reviewing previous lessons preparatory to a launch (Intelligent Virtual Station, 2017).

Although space agencies are reluctant to publicize human errors made on space missions, some indication of what types of errors can be expected in the future can be found in the 2007 incident aboard the ISS when two of three Russian computers installed on the station failed. As a result, knocking out the atmosphere control system as well as the autopilot's ability to hold the station steady with fire maneuvering thrusters (Oberg, 2007). An internal NASA investigation concluded that "On 13 June [2007], a complete shutdown of secondary power to all [three] central computer and terminal computer channels occurred, resulting in the loss of capability to control ISS Russian segment systems" (Oberg, 2007, Para. 3).

In response, Russian authorities alternatively blamed NASA for "zapping their computers" with "dirty" 28-volt power generated by newly installed solar power panel array or that the recently increased mass of the ISS was causing excessive energy as a result of the station's orbital speed as it traveled through the Earth's magnetic field (Oberg, 2007). According to Oberg (2007), "These were the first of many bad guesses by top Russian program managers that would distract engineers trying to get at the real problem" (Para. 5). The actual cause of the computer crash was further obscured by the stop-gap measure of using jumper cables to bypass two of the three failed computers which led Russian crew members to believe that the source of the problem was external (Oberg, 2007).

The source of the problem turned out to be a design flaw with the connection pins which had corroded. After an exhaustive disassembly and manual inspection of all of the hardware components by Russian and American crew members, the design flaw was identified and

replacement parts were dispatched via a re-supply mission (Oberg, 2007); however, this alternative would not have been available on a Mars mission. For instance, and the inspection and analysis of the root problem would have been facilitated by enhanced ergonomic design using virtual model technology.

In 1983, NASA created the Man-Systems Division within its Life Science Directorate, which was tasked with identifying important man-machine interface issues that need to be taken into account in the design of living habitats for the ISS. The stated goal of this initiative was to “enhance human productivity and reduce the need for later design changes” (Kitmacher, 2002, p. 8). The Man-System Division subsequently clarified its mission as follows: “Habitability is concerned with providing a Space Station facility that provides a comfortable, functionally efficient habitat. Attention must be given to the morale, comfort and health of crews” (Kitmacher, 2002, p. 8). According to Kitmacher (2002), the Man-System Division also conceded that,

“the habitability architecture design concerns are mainly with respect to the fixed architectural elements of the Crew/Space Station interfaces such as the geometric arrangements of compartments and the interior appointments, decorations; provisions for work or off-duty stations; stowage and retrieval provisions, privacy; and traffic patterns, displays, and access and egress provisions” (p. 8).

Notwithstanding their important mandate and these stated goals, the two-dimensional modeling technology available at the time limited the Man-System Division’s attempts to integrate ergonomic design into these architectural elements. During the time of Space Station architecture development in the 70s and 80s, computers were still well in their infancy in regards to technological superiority. (Kitchmacher, 2002). More to the point, this early design initiative did not consider these issues from the perspective of the crew members who would actually be

using these systems, and it is reasonable to posit that the application of more powerful three-dimensional modeling technology could vastly improve the ergonomic design of those elements that continue to pose the most problems for crew members today.

While it may appear intuitive to the average observer that crew members on board the ISS would like to be able to look out a window to view their surroundings and the Earth below given the basic human needs to orient themselves to their environment and avoid the increased sense of confinement and isolation that would otherwise result, this issue was actually a point of significant controversy during the early design phases. Despite reports from Skylab astronauts that the time spent in their wardrooms looking out their window, observing and photographing the Earth was the most enjoyable time spent on their missions, the need for windows and “windowed workstations” remained a point of contention among designers.

Despite the extra expense, the utility and the need for such resources, though, became apparent after NASA engineers listened to crew member accounts and preferences for their working and living accommodations in space. For instance, Kitmacher (2002) reported that “Astronaut Gordon Fullerton expressed the viewpoint of the flight crew very simply: ‘give me a window and binoculars any day over a high tech solution’” (p. 13). As a result, NASA designers modeled and evaluated a number of different configurations and developed a cupola viewport that is currently in use on the ISS today (Kitmacher, 2002). Although the fundamental human need to be able to look outside an environment may appear unimportant, it is clear that this human limitation, as well as others, must be considered during the design phase for all aspects of the living and working environments on the ISS and virtual modeling technology has proven effective in achieving these outcomes.

### **Conclusion**

Although significant parts of the International Space Station were designed using technology from the 1990s, the research showed that emerging virtual modeling technologies such as the human-out-of-the-loop (HOOTL) computational simulations and Intelligent Virtual can aid in enhancing ergonomic design elements on the International Space Station today and in the future. It is clear that the current ergonomic design issues have caused a myriad of problems for space crew members. Current and past research has shown a recurring theme that human factors beyond just life support systems must be taken into account when designing future space habitats. The unique environment of microgravity also means that the importance of using virtual modeling simulations to improve the previous ergonomic design for the ISS remains extremely applicable. Notably, it must extend beyond the conventional two-dimensional solutions used on Earth to include three-dimensional living and working areas in order to optimize any available space while integrating the human agent aspect of space travel.

### **Comprehensive Exam Question #4**

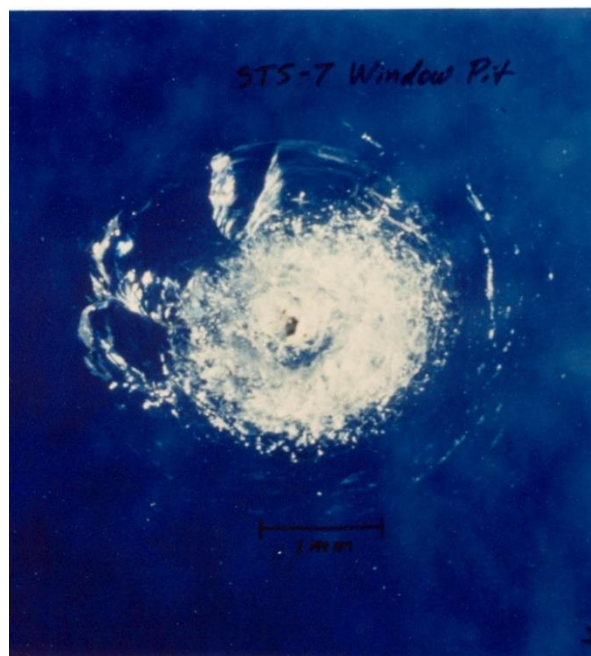
**Statement of the question:** How should current debris mitigation methods change to prevent future catastrophic collisions? Does a correlation exist between an increase in space debris and potential collisions within the next 200 years, based on projected satellite deployments in low Earth orbit? What are the implications that space debris plays in today's geopolitical environment?

### **Research and Analysis of the Question**

One of the most serious problems facing space travel today is the amount of debris that is in Earth orbit. According to estimates published by NASA, there are more than a half million pieces of debris the size of a marble or larger as well as 20,000 pieces of orbital debris that are

larger than a softball which is monitored by the Joint Space Operations Center (USSTRATCOM) as they orbit around sensitive spy and communications satellites.

It is important to note that this debris travels at sufficient hyper velocities (17,500 mph) and often causes catastrophic damages to spacecraft or satellites (Space debris and human spacecraft, 2017).



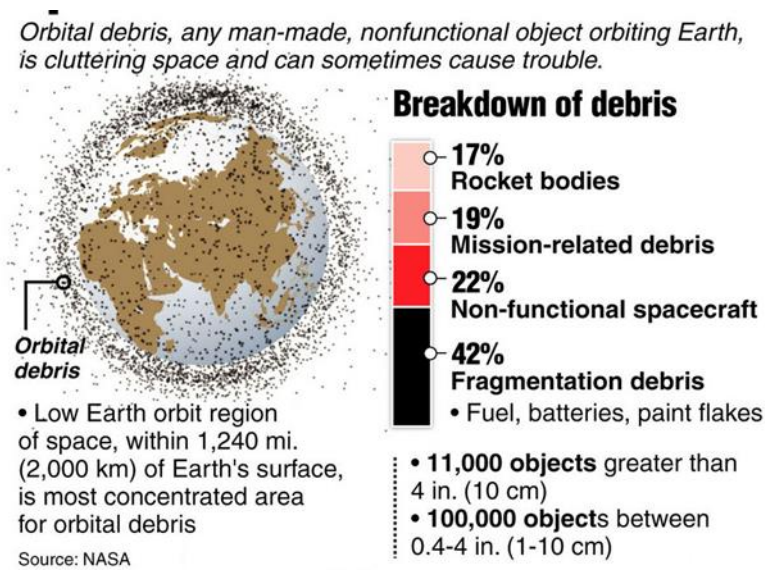
**Fig 6.** Window Pit from 0.2mm Paint Fleck (NASA.gov)

In fact, even paint chips can cause significant damage traveling at these speeds, making the need to identify the current status of “space junk” an important issue for space agencies around the world. One such incident that was particularly noted was in 1983, the Space Shuttle Challenger crew of STS 7 had just completed their mission when NASA technicians discovered one of the space shuttle windows had been damaged by a paint fleck (0.2mm) in diameter traveling at hypervelocities and it caused a vast amount of damage to the spacecraft window (Figure 6) below.



**Current Status of Orbital Debris**

As shown in Figure 7 below, outer space may be infinite, but the region surrounding the Earth is not and the density of orbital debris has steadily increased since the dawn of the Space Age.



*Fig 7. Current levels and breakdown of orbital debris (GeoSats, 2017)*

Indeed, it is surprising that there have only been three documented accidental collisions between catalogued space objects from 1991 to 2005. According to Liou and Johnson (2006), a collision in “ (January 2005) was a 31-year-old U.S. rocket body and a fragment from the third stage of a Chinese CZ-4 launch vehicle that had exploded in March 2000” (p. 343). The most recent were the 2009 catastrophic collision between Iridium 33 communications satellite and the Cosmos 2251 Russian military satellite which had been inactive since 1993. The collision occurred in near-earth orbit which is close to the highest spatial density and the area you would expect this type of collision to occur due to the congestion in the

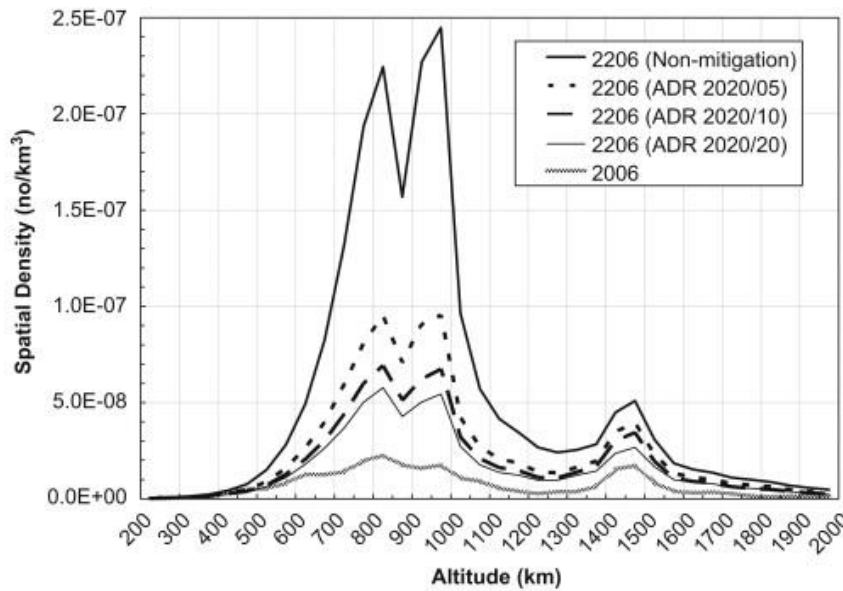
region. Iridium 33 had a mass of about 60kg and the Cosmos 2251 had a mass of 900kg at the time of impact (Wright, 2009).

To date, the U.S Space Surveillance Network has identified 1800 new debris in the orbital plane which is about 10cm in diameter and the rest are in a mode of being tracked. The orbital planes of these satellites were perpendicular which didn't make a difference in the outcome other than the collision velocity which far exceeded that for a catastrophic breakup (Wright, 2009). Consequently, the more revolutions that the debris goes through, the higher the increase in the debris count due to the numerous collisions that would be expected to occur. High orbital plane propagation is to be expected due to the expansion of the debris that doesn't stay in the same orbit due to the collisions (Wright, 2009). The Cosmos 2251 satellite debris had a lower inclination, therefore, had a higher differential procession rate and the debris expansion and dispersion rates are expected to be higher than the Iridium 33 debris over time. This scenario in a 2-year time span places the debris cloud expansion over the entire Earth orbit. Coincidentally, 75% of the Iridium 33 satellite was made mainly of composite materials so this debris will decay more rapidly if regular solar activity persists (Wright, 2009).

### **Correlation between an Increase in Space Debris and Potential Future Collisions**

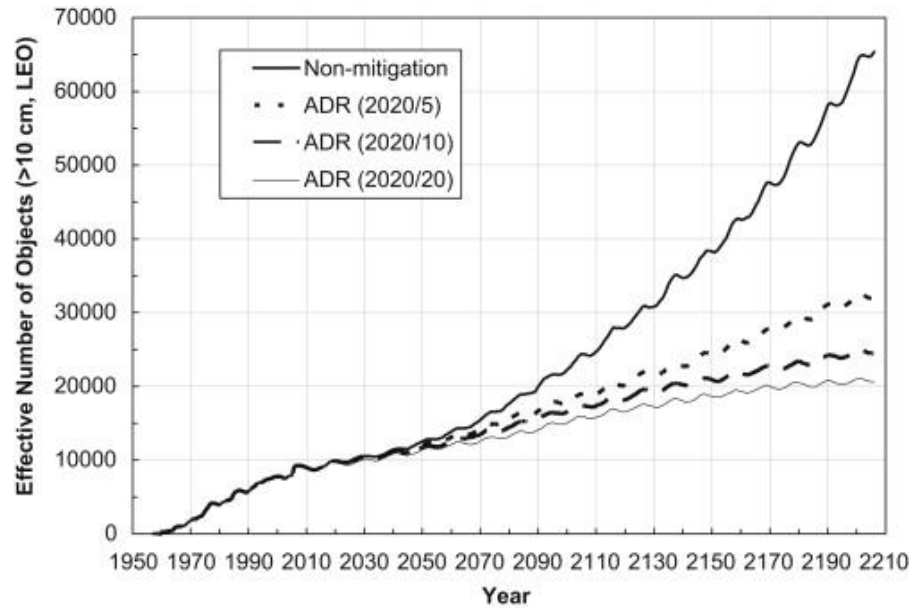
An analysis of data from recent studies concerning estimated spatial density distributions for objects 10 cm and larger, for three different years, 2004, 2014 and 2210 as well as the effective number of objects, 10 cm and larger, between 900 and 1000 km altitudes based on the LEO to GEO Environment Debris model (LEGEND) simulation is illustrated below in Figure 8 and Figure 9 (Liou & Johnson, 2006). The study by Liou and Johnson (2006) assumed that there would be no new rocket bodies and spacecraft launched after December 2004 and that there would be no future disposal maneuvers allowed for existing spacecraft because these vehicles typically do not possess such capabilities. The quantitative data analysis also assumed that the

rate of satellite explosions would naturally decrease to zero within a few decades due to the continuing aging of the current satellite population (Liou & Johnson, 2006).



**Fig 8.** Spatial density distribution of objects 10 cm and larger in LEO. The bottom curve represents the LEO environment at the end of 2006. The other four curves, from top to bottom, are the predicted environment in 2206 from the non-mitigation ADR 2020/5, ADR 2020/10, and ADR 2020/20 scenarios \*ADR (Active Debris Removal)  
(Liou & Johnson, 2007)

The results of the simulated 10 cm and larger debris populations in low Earth orbit (LEO) defined as the region between 200 and 2000 km altitudes during the period 1957 through the end of an estimated 200 year future projection period showed that collision fragments continue to repopulate the amount of orbital debris that decays due to solar radiation pressure and atmospheric drag. In that way maintaining the population of LEO orbital debris at an approximately constant level (Liou & Johnson, 2006).



*Fig 9. LEGEND-simulated LEO debris population (objects 10 cm and larger) as functions of time from the four test scenarios (1957 to 2206). Non-mitigation scenario is used as benchmark for comparison assuming Active Debris Removal starts in 2020 (Liou & Johnson, 2007)*

The situation worsens, though, after 2055 due to the creation of new orbital debris fragments at a faster level than the decay rate. In addition, the study also predicted that an average of 18.2 collisions (10.8 catastrophic, 7.4 non-catastrophic) would occur over the next 2 centuries. Further, the results of the Liou and Johnson (2006) study also showed that approximately 60% of all catastrophic collisions take place in the region between 900 and 1000 km altitudes (Figure 8) which will result in a significant increase in this region over the next 2 centuries (Liou & Johnson, 2006). In fact, given that this statistical model assumed that there would be no new launches after 2004, the problem of orbital debris will likely be far worse than these projections indicate with the continuation of space launches (Liou & Johnson, 2006).

Furthermore, a number of studies performed during the period from 1991 through 2001 indicated that even if all launches were stopped today, the amount of orbital debris will continue

to increase due to expected increase in collisions between orbital debris over the next 200 years. In this regard, Liou and Johnson (2006) conclude that “Even if launch operations were to cease today, the population of space debris would continue to grow. Further, proposed remediation techniques do not appear to offer a viable solution” (p. 341). This proves what is currently known as an exact correlation between an increase in space debris and potential collisions within the next 200 years, based on projected satellite deployments in low Earth orbit. Given these odds for orbital debris to damage functional satellites and cause human casualties in space, NASA needs to remain vigilant in tracking this debris, a term used to refer to any artificial object in space that is no longer functioning in a useful fashion, including abandoned launch vehicle stages, nonfunctional spacecraft, mission-related debris and fragmentation debris (Space debris and human spacecraft, 2017).

### **Implications of Space Debris on the Current Geopolitical Environment**

There have also been some long-term solutions proposed which are supported by international space agencies to better manage future spacecraft and the manner in which they are disposed of as well as remediation initiatives for the current population of orbital debris. Unfortunately, these proposals have been constrained by technological and financial limitations. For example, one strategy that has been advanced by a number of agencies from different countries (i.e., NASA, U.S. Departments of Defense and Transportation, U.S. Federal Communications Commission, European Space Agency, Inter-Agency Space Debris Coordination Committee, and the Japan Aerospace Exploration Agency) with interests in space and this is to limit the orbital lifetimes of vehicles to less than 25 years. Although this strategy would limit future debris growth, it would not be enough to address the full extent of the problem, which is the eventual collisions of spent rockets and non-operable satellites which lead to massive debris propagation-increasing the problem tenfold (Liou & Johnson, 2006).

The only viable alternative, Liou and Johnson (2006) argue, is the “remediation of the near-Earth environment, i.e., the removal of existing large objects from orbit [to] prevent the undesirable effects predicted in the present study” (p. 5). Current technologies that could be applied to this alternative solution, though, are either cost ineffective or involve massive logistical issues that would prevent their widespread deployment for the foreseeable future (Liou & Johnson, 2006).

### **Conclusion**

At present, the research showed that there is more than a half million pieces of orbital debris the size of a marble or larger and 20,000 pieces of orbital debris larger than a softball already in place. Current projects indicate that even if all launch operations ceased today, the amount of orbital debris will continue to increase due to collisions that outpace the decay of orbital debris due to atmosphere friction after their orbits degrade. Although the problem is well recognized and understood, there is less consensus concerning how best to solve this significant problem. The proposed limitations on the life spans of new satellites and spacecraft will therefore only be effective at limiting the amount of new orbital debris that is created but will not address the enormous amount of debris that is projected to be created for the future. Furthermore, Cosmos 2251 and Iridium 33 satellite collision only added onto the debris population and is projected to produce 200,000 pieces of new debris in their respective orbital planes. As a consequence, the ISS will have to do more frequent debris avoidance maneuvers than its usual 2 projected every year, additionally this means that the low Earth orbit environment has reached such an apex of instability that orbital debris collisions will start to seem like an everyday occurrence. Something that we should work diligently to avoid if we want to keep our future exploration aspirations alive. In sum, what remains true is the fact that orbital debris mitigation is a serious issue that needs to be dealt with sooner than later. All things

considered, there remains an overarching need to identify cost effective remediation strategies for orbital debris in the long term and more aggressive efforts to reduce the amount of new “space junk” that is being placed in Earth orbit, because setting off a nuclear warhead in space is not the approach to solving this particular issue.

### **Comprehensive Exam Question #5**

**Statement of the question:** “How can microgravity induced physiological issues to be counteracted to support future long duration space missions?”

### **Research and Analysis of the Question**

After more than half a century of space travel, our aspirations to explore the unknown have not been in vain. Human spaceflight has made numerous discoveries, not only about our vast universe but most importantly about human physiology in the space environment. Current scientific evidence states that long duration space travel in microgravity induces a myriad of physiological issues that are comparable to the ageing process and disease. The fact that weight-bearing joints don’t maintain loads, this is causing musculoskeletal and cardiovascular function deconditioning in astronauts. What remains of concern in this current scenario is the individuals involved may never recover post spaceflight, meaning that the development of countermeasures to decrease these issues remains of the utmost importance.

### **Types of Space Physiology Problems**

Strangely enough, even the healthiest and heartiest humans in the prime of their lives can be regarded as frail and replete with limitations when faced with the hostile environment of space. Although there is a growing body of research concerning the adaptation of crew members’ bodies to microgravity environments, there remains a dearth of timely and relevant studies concerning the harmful cumulative effects of high levels of ionizing cosmic ray energy on human cells and tissues during long duration space flights (Setlow, 2003). Observations of

astronauts travelling on the Space Shuttle and Russian cosmonauts' long-term visits to the Mir space station indicated that time spent in “Zero G” has serious effects on bone and muscle physiology and the cardiovascular system (Setlow, 2003). In addition, the flow of blood to the brain increases in microgravity environments, which can result in reduced intravascular pressures and volumes in crew members’ legs as well as elevated intravascular volumes and pressures in the upper body due to cephalad fluid shift (Hargens et al., 2013).

The studies to date confirm the rapid loss of bone in space as well as a corresponding risk for the formation of kidney stones, but these studies have reported mixed results concerning the most efficacious interventions that can be used in space (Buckey, 2006). Likewise, a study by Zhu, Wang and Liu (2015) found that some astronauts and cosmonauts have experienced cardiovascular problems during and following space missions. For example, Zhu et al. (2015) report that “One of the astronauts on Apollo 15 suffered myocardial infarction after spaceflight, and another astronaut on Soyuz had to go back to Earth due to the severe cardiac arrhythmia” (p. 793).

In addition, space physiology problems are further exacerbated by several environmental factors such as a sense of isolation and narrow working environments (Zhang, Li, Liu, Jing and Wu, 2015) as well as high concentrations of CO<sub>2</sub> and low lights levels (Buckey, 2006). Finally, another space physiology problem that remains understudied is the potential for direct damage to cells on the human immune system, with the current estimated rate equaling or exceeding that required for mutations (Setlow, 2003). This human limitation may become one of the more important problems facing future long duration space missions since there is the possibility of what is termed the “bystander effect” to result in significantly greater damage to neighboring cells over time (Setlow, 2003). In fact, a study by Stowe, Sams and Pierson (2011) found that there are significant differences between the neuro-immune responses that have historically been



experienced even during shorter duration space missions such as those on the Space Shuttle as well as the neuro-immune responses that have been historically experienced on longer duration ISS missions, findings that reinforce the limited amount of other research to date concerning the salience of mission duration on space physiology problems.

### **Countermeasures for Space Physiology Problems**

There is a growing body of research concerning the types of physiological problems that are typically experienced in weightless and microgravity environments, and there is a general consensus that additional space physiology research is needed today (Buckey, 2006). Though, crew members receive specialized rehabilitative treatments upon their return to Earth, the most effective interventions developed to date for use in space are the use of treadmills and bungee cords to keep crew members in place, advanced resistance exercise devices and an ergometer (Buckey, 2006). Nevertheless, studies continue to show that even with the most aggressive countermeasure programs, crew members on space missions still continue to experience high levels of bone density loss and it was stated by Hargens et al (2013), “a 50 % reduction in skeletal muscle protein synthesis during the first 2 weeks of bed rest, despite a stable diet and no significant changes in serum cortisol, testosterone, or insulin.” The rates that astronauts are experiencing this bone loss is far more alarming during spaceflight than during Head-down tilt (HDT) bed rest which is an Earth based test model for studying the physiological changes occurring in weightlessness during spaceflight (Hargens et al., 2013).

In current studies, volunteers are subjected to a strict HDT of 6<sup>0</sup> degrees for 3 months and the purpose is to imitate cephalad fluid shift that is experienced by astronauts in microgravity. Individuals involved in the study, experience a sudden decline in aerobic capacity due to decreased blood circulation being in the 6<sup>0</sup> degree orientation (Hargens et al., 2013).

These are just the many studies that are being carried out in order to develop the best

countermeasures to these physiological issues that could spell disastrous for a long-term Mars mission. At any rate, a vital countermeasure that has been utilized to maintain muscle, bone, and decreases intracranial pressure during spaceflight has been exercise. As mentioned before, there are numerous devices that facilitate this endeavor and one of them is the Lower Body Negative Pressure (LBNP) device. The LBNP is a device that places stress on the cardiovascular system similar to what it experiences in Earth's gravity (Hargens et al., 2013). The device covers the individual from his/her feet to the waist and forms an air seal, a pump then takes all the air out and creates a negative pressure in the airtight sealed chamber. The proven hypothesis is thus, the cephalad fluid shifts from the individual's upper extremities (head) to their lower extremities (legs) in lieu of counteracting muscle atrophy and intracranial pressures induced by microgravity (Hargens et al., 2013).

Although LBNP is a great countermeasure to counteracting the detrimental physiological effects of microgravity. It has to be done at 120 minute increments in order for the astronaut to get a 30 minute lasting positive effect which is by no means practical as a long-term method for space crew members on long duration spaceflights that could last up to 6 months. The hypothesis of creating an artificial gravity environment remains the most illustrious within this arena. The hypothesis states that if a 1G or Earth gravity environment is recreated then muscle atrophy, bone density loss, and visual impairments caused by intraocular pressure would be eliminated. This hypothesis sounds good in theory, but engineers that understand the physics that go into utilizing this method know that it's far less practical once the parameters are put into place in the space environment. It remains evident that artificial gravity can be recreated in space as we saw Russia do it during the Space Race, but what many fail to understand is the significance of the rotation rates that a short-arm centrifuge system would have to undergo to produce the effect and the necessary adaptations'. Astronauts would have to endure initially

dealing with the neuro-otological and Coriolis effects (Rittweger et al., 2015). Furthermore, certain exercise devices such as the treadmill would provide inadequate due to the cross-coupling and Coriolis effects (Rittweger et al., 2015).

It comes as no surprise that the importance of these issues has become more pronounced in recent years as space missions have gotten longer and researchers continue to plan for a Mars mission by the early to late 2030s. For instance, Vakoch (2011) points out that, “An understanding of the problems and their amelioration is essential if a man desires to occupy space for extended periods of time. Even more important from a scientific perspective, it seems likely that significant advances in our basic knowledge of human interaction” (p. 9). Therefore, developing a timely and informed solution to this research predicament represents an important step in achieving the goal of a Mars mission and extended stays on the ISS.

### **The Effects of Space Physiology Problems on Crew Member Performance and Functioning**

Reference is made to the different types of unsafe acts described heretofore (i.e., taking shortcuts, being overconfident, initiating a task without complete instructions, ignoring safety procedures, poor housekeeping practices, mental distractions from tasks, and the failure to pre-plan the work) (Unsafe Acts, 2016). As also noted above, long duration space missions are inherently harmful to crew members’ physical and psychological states despite the in-flight countermeasures such as treadmills and private communication opportunities that are being used to address these problems. Many of these problems can be expected to contribute to the potential for unsafe acts due to crew exhaustion, distraction, inattentiveness or simply a sense of overconfidence in their abilities (Hargens et al., 2013; Setlow, 2003, Zhang et al., 2015, Zhu et al., 2015) which could result in taking shortcuts to established protocols and safety procedures. The purpose of which may not be readily apparent to them and this would by every means affect mission completion.

## **Human factors and space physiology problems**

Beyond the foregoing issues, individual crew member attitudes about attire may also have an effect on their physiology during space missions. For example, according to one NASA worker:

“Astronauts spend more than two hours a day exercising. A lot of that time is running on a treadmill. Even though there is no noticeable pull from gravity, there is still inertia. So while they are running on the treadmill, their rib cage is constantly changing its direction of motion and other more delicate parts are resisting those changes. That's a lot of stress, so sports bras are commonly used during exercise. When not exercising, it is up to the preference of the individual astronauts and not really our business. (Frost, 2013, Para. 3)”

Likewise, crew member attitudes about the quality and selection of food can be reasonably expected to affect their appetites and eventually their health, and this issue assumes even greater significance when multinational crew members are involved. This is a clear indication that space physiological problems go well beyond the current countermeasures designed to combat intracranial pressure and muscle atrophy associated with microgravity, space physiological problems are now clearly seen to be affecting the overall astronaut lifestyle as a whole.

### **Conclusion**

As previously mentioned, space physiological issues continue to be detrimental to space crew physiological profiles and current methods aren't aiding in the decrease of muscle atrophy or bone density loss. In fact, cardiovascular issues continue to be on the rise due to cephalad fluid shifts and orthostatic intolerance continues to plague returning astronauts for months on end after their arrival in Earth's gravity. Current studies in Head-down tilt bed rest continue to show the decline in aerobic capacity and physical de-conditioning that astronauts are experiencing in

the microgravity environment. Orthostatic intolerance has been attributed to cardiac mass and decreased cardiac functioning that occurs during the first 2 weeks in the microgravity environment which clearly demonstrates the unsafe effects of microgravity on humans. The low body negative pressure (LBNP) device which provides load bearing independent of gravity has shown to have positive effects on orbit to provide 6-8 hour of relief in regards to shifting fluid back to the lower extremities. The idea of artificial gravity to counteract the gravitational blood pressure gradients as one is exposed to microgravity still remains in the theoretical arena and if development is underway, then designers have to be cognizant of the limitations of the short-arm centrifuge system and its effects on astronaut physiologies. The research demonstrated that space physiology goes beyond the physical and taps into the psychological profiles of the space crew members involved in these long duration missions, the research did, however, prove the null hypothesis to be the currently accepted truth. Research shows that current methods including; advanced resistive exercise devices, LBNP, and treadmills used to counteract microgravity induced physiological issues are not proving very effective in preventing physical de-conditioning. For e.g. muscle atrophy, bone density loss, visual impairments and cardiovascular arrhythmias meaning that any planned manned mission to the Red planet would be too perilous and futile.

### Summary

The research was consistent in showing that the long duration spaceflight does indeed have a number of detrimental effects on crew performance and functioning, but there remain serious limitations concerning what steps should be taken to facilitate long-term spaceflight missions. The current countermeasures that are in place will likely be inadequate to ensure the safety and well-being of crew members on extended missions and more research is needed to identify viable solutions. The analysis concerning what considerations are involved in manual rendezvous missions and docking in space likewise showed that system designers are faced with several human factors that must be taken into account in order to support these missions. On the research topic of emerging virtual modeling technology helping in solving the ergonomic design problems of the International Space Station; again by taking empirical observations and feedback from experienced crew members into account. Additionally, current research shows that low Earth orbit is populated by tens of thousands of pieces of “space junk” that threaten the safety of satellites and even manned missions. However, there are clearly no viable plans underway to address this problem which is expected to become even more severe over the next century if active debris mitigation processes are not put in place amidst the Cosmos 2251 and Iridium 33 satellite collisions. Finally, it is reasonable to conclude that, like the remediation of current and future levels of orbital debris, there are a number of significant space physiology problems that have been identified to date. Nevertheless, there remains a profound need for additional research concerning how best to address these on longer duration missions like those to the Martian planet. The countermeasures that have been used thus far, to include diet supplements and advanced resistive exercise devices to reduce bone loss and muscle atrophy are only partial solutions and still wouldn't be practical for long-term missions. The research in short-arm centrifugal artificial gravitational systems is still in its infancy but remains elusive in solving

microgravity induced physiological effects due to the negative effects that follow initiation of the artificial gravity environment in a spacecraft. The research covered various subjects in the aerospace arena that have yet to gain momentum in regards to conclusive research necessary in finding solutions to the issues proposed. On the other hand, a definite need is evident considering the significance of these solutions in not only advancing manned space flight but accomplishing our future space exploration goals. For this reason, industry experts need to show more vigilance and proactivity in resolving these issues as they do with those that related to design and development of space habitats and launch propulsion systems for long-term spaceflight.

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