CHAPTER

# Habitability and habitat design

# 15

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## CHAPTER OUTLINE

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## INTRODUCTION

During a space mission, astronauts operate a complex vehicle and face an extremely dangerous environment, while their life, from what they eat, to how they move around, work and sleep, is much different from that on Earth. The Oxford Dictionary (2011) defines habitat as “the natural home or environment of an animal, plant, or other organism” and habitable as “suitable or good enough to live in.” Habitability is “the quality of life in an environment” (SSP 50005, 1999), i.e., in a habitat, and it is related to human factors. A space habitat designed without considering human factors has a low level of habitability, or in other words, the quality of life in such habitat is low. For short space missions, sacrificing habitability for the sake of meeting mission objectives is acceptable, but for long-duration mission, providing “adequate” habitability is essential to ensure human performance. “Maintaining skilled performance during extended spaceflight is of critical importance to the health and safety of crewmembers and to the overall success of the mission” (Connors et al., 1985).

The relationship between habitability and human performance is an old concern. An early study performed in the sixties on spacecraft habitability included the following quotation and comment. “*The more modern the ship and the greater the need for intelligence in her crew, the more objectionable she seems to become in point of quarters for the men, until we have about reached the point where it is well to call a halt on certain disastrous tendencies in the direction of the utter disregard of what intelligent men are capable of putting up with…it will be best to point out some changes which are needed in the internal arrangements and discipline of our ships, in order to secure the creature comforts to the men under all conditions of service, and thus render the ships habitable and attractive. The physical condition of the men, when it comes to action or to conditions of war, is of greater moment than the…extra knots…for which we are asked to sacrifice so much.* This quotation is not the work of a human factors specialist in space cabin design, nor that of a modern naval architect. It was written in 1891 by Ensign A. P. Niblack of the U. S. Navy, as part of an essay concerning the habitability problems aboard Navy vessels” (Celentano et al., 1963). Indeed, from naval vessels to spacecraft, habitability has been well known to be a key element affecting performance and safety.

In early space missions, astronauts had a rather passive role while the mission control center was the primary operational element. Later, with Shuttle and ISS, the crew on board took on active duties like performing extravehicular activities, experiments, and onboard maintenance. However, they continued to rely on ground operators to keep the system running and for technical support. In future missions to Mars, the role of the mission control center will be de-emphasized. because of delayed communication with ground, and astronauts will have complete autonomous control of the system. System safety and mission success will very much depend on crew performance, and performance will among others depend on habitability.

On long-duration and long-distance missions, the social confinement in a restricted and isolated community, the environmental monotony of the artificial habitat, “the Earth-out-of-view phenomenon” (Kanas and Manzey 2008), and the lack of privacy can cause discomfort, boredom, and mental drowsiness, and increase the risks of human error. In this context, plans for supporting the quality of life in the habitat are the basis for ensuring performance and safety of the crew.

This chapter is an introduction to space mission habitability, habitat design, and related effects on human performance. It includes some general concepts and guidelines as well as two specific sections dedicated to the special topics of noise control and radiation shielding, which are critical for health and safety on long-duration missions.

## 15.1 HABITABILITY

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### 15.1.1 DEFINITIONS AND ELEMENTS

There are several definitions of habitability in a space mission, where the term mission is meant to aggregate system, operations, duration, and goals.

An early proposed definition is habitability as an "equilibrium state, resulting from human-machine-environment-mission interactions which permits man to maintain physiological homeostasis, adequate performance, and psychosocial integrity" (Fraser, 1968, p. V). A high level of habitability is the optimal condition for life, while low level of habitability only allows for survival. In the "NASA's Living Aloft Human Requirements for Extended Spaceflight" habitability is defined as "a level of environmental acceptability" (Connors et al., 1985, p. 59).

Messerschmid, a former European astronaut, defines habitability in a space mission as the living conditions concerning both work and domestic environment and correlates habitability with crew's performance, in turn defined as the "crew's ability to fulfill its tasks correctly and in a reliable manner" (Messerschmid, 2008). According to Messerschmid the other factors that influence performance are physiological conditions, working capacity, and psychosocial aspects (Messerschmid and Bertrand, 1999). For Blume Novak (2000), "habitability is defined by the physical interface between the human user and the system/environment; habitability can also be described as the usability of the environment."

The standard used in the ISS program defines habitability:

> *"the quality of life in an environment. It is a general term which denotes a level of perceived environmental acceptability. The term includes quality standards to support the crew's health and well being during the duty and off–duty periods. The basic level of habitability deals with the direct environment, like climate, food, noise, light, etc., influencing primarily human physical condition. The extended level of habitability is introduced to take care of the long–term condition of the on–orbit stay time and supply not only the individuals' physical health but also the mental/psychological health. Experience has shown that with the passage of time deleterious effects of isolation and confinement gain prominence."*
>
> **(SSP 50005, 1999).**

In other words, the ISS standard defines habitability as a key factor to support physical and mental/psychological health on long-duration missions.

The three main elements to assure good habitability are (Häuplik-Meusburger, 2011):

- *Usability*: The layout, configuration, and design of extraterrestrial habitats assure efficient, user-friendly and trouble-free habitation over a specified or planned period of time.
- *Livability*: The habitat provides maximum living space even within a minimal limited and socially isolated volume for the individual and the crew.
- *Flexibility*: The habitat allows adjustments according to the requirements of the users, to changing mission tasks as well as unforeseen social and mission-related changes.

Finally, the design requirements for habitability could be influenced by the cultural background, in particular "some aspect of habitability, such as religious practices, personal space, nutritional requirements, or palatability, temperature, and illumination can vary across cultural groups" (Blume Novak, 2000).

## 15.1.2 MISSION FACTORS AND REQUIREMENTS

### 15.1.2.1 MISSION DURATION

During early space missions with tiny capsules, few activities required moving around and most of the time the astronaut was strapped to the seat. The design of the habitat was "seat-driven." The situation changed with the introduction of space stations and long-duration missions. For long-duration missions (months or years), habitability is achieved by applying human factors in the design of living and working conditions, while for short-duration missions lower habitat standards are acceptable, and the focus is on ergonomics (ergo = work), which is the application of human factors to the working conditions (Messerschmid and Bertrand, 1999) (Fig. 15.1.1).

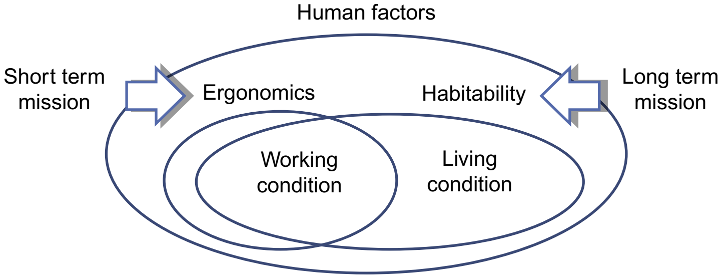

**FIG. 15.1.1**

Relationship between human factors, habitability, and ergonomics.

"Habitability requirements for space flights are driven by mission duration" (Woolford and Mount, 2006). "For brief periods, almost any arrangement that does not interfere with the health of the individuals or the performance of their jobs would be acceptable. Over the long term, conditions must support not only individuals' physical, but also their psychological health" (Connors et al., 1985).

### 15.1.2.2 DISTANCE FROM EARTH

Another important factor that influences the habitability of a space mission is the distance from Earth. There is quite a difference between being on a 56-million km journey to Mars and just orbiting Earth at 400 km of altitude. The distance from Earth strongly affects habitability with regards to safety (i.e., leaving the radiation shielding of Earth magnetic field), logistics, communication, and emergency constraints. Between Mars and Earth there is a 44-min communication delay, no live conversation will be possible with relatives, mission control center, or psychological support team. As Kanas explains, in order to "counter feelings of monotony, isolation, and behavioural health issues like asthenia astronauts will not be able to receive surprise presents and favourite foods, delivered via re-supply vehicles, or to increase the contact with people on Earth, and ground-crew counselling or psychotherapy like on

ISS. Or even to receive the arrival of visiting astronauts and cosmonauts, that break the monotony and provide stimulation and assistance in performing mission activities" (Kanas and Manzey, 2008, p. 193), Thus, decking out the Martian-bound craft with family photographs, special trinkets, books, and even plants may be a crucial element for a mostly monotonous extraterrestrial road trip. If someone becomes sick, either physically or mentally, the crew has to be ready to cope with the situation in full autonomy.

## 15.1.3 HABITABILITY AND PSYCHOLOGICAL STRESSORS

A study performed by NASA in 1985 identified the following five major topics related to human factors that can interact with crew safety: protocols, habitability, work-related issues, crew incapacitation, and personal choice (Rockoff et al., 1985). Stressors related to those factors can cause degradation of human performance, which in turn can lead to human errors and mishaps. There are two lines of defense: the first by implementing countermeasures against stresses, the second by implementing design and operational controls against errors (see Chapter 8). Table 15.1.1 summarizes psychological stressors and habitability countermeasures on long-duration missions.

Stresses due to poor habitability can lead to anxiety, claustrophobia, sleep disturbances, fatigue, irritability, morale deterioration, and discomfort. Those conditions may then result in impaired response, mistakes in perception, judgment and action, failure to communicate or coordinate (Rockoff et al., 1985).

## 15.1.4 PRIVACY AND PROXEMICS

### 15.1.4.1 PRIVACY

As part of an investigation of habitability needs in future long-duration space missions, the author interviewed astronauts and engineers involved in the international space station program. Most astronauts would have liked better privacy, while engineers considered larger volumes more important. In future space missions, qualitative aspects of habitability such as privacy should be driving the design because they reflect the real needs of the astronauts (Schlacht 2011).

Usually, privacy is considered as the feeling associated with a private physical territory. It is not a physical quantity but rather a quality of experience related to the need for solitude, intimacy, anonymity, and reserve (Westin, 1967). In other words, the need to express personal feelings and communicate with our self or selected person. There are two main kinds of privacy: acoustic and visual. But privacy also relates to physical distance between individuals, and to access to private data.

From an architectural viewpoint, acoustic privacy is easier to implement, for example by using headphones or sound-absorbing materials. Visual privacy requires some form of divider, which can be mobile or temporary like rolling blinds. To achieve visual privacy, it is not necessary to completely cover a person from his or her visual surroundings, usually it is sufficient to prevent being observed more

**Table 15.1.1** Psychological stressors and related habitability countermeasures

| Psychological stressor | Habitability countermeasure |
|---|---|
| Lack of personal space\ lack of privacy | Provide individual, separate sleeping/personal quarters w/ auditory isolation (mandatory) and physical separation (if possible) for each crew member<br>Separation of private spaces from spaces allocated for common, social areas and congested translation paths<br>Visual separation of private spaces from each other to allow for perception of increased privacy<br>Dedicated, private area for waste and hygiene with hygiene areas away from dining area and medical station<br>Separation of waste and hygiene compartment area from translation areas |
| Feeling of "crowdedness" | Appropriate task scheduling/task location<br>Dedicated translation paths in integrated environment<br>Increased volume or other dimensions to increased actual/ perceived space<br>Rotating shifts |
| Lack of individual controls | Place individual controls over temperature, ventilation, or lighting, and distribution vents in crew quarters and at workstations |
| Lack of reconfigurability | Reconfigurable accommodation, and modular design for multiple activities for cultural differences and personal preferences |
| Lack of stimulation/ sensory variability | Windows, virtual windows—camera with projections of space, video of terrestrial footage, telescope, "holodeck" or other virtually immersive environment<br>Increased spatial vista within habitat<br>Lighting, colors, and other visual countermeasures to increase sensory stimulation<br>Greenhouse or other introduction of plants and natural elements for tactile, visual, gustatory, olfactory<br>Different surfaces in the interior to maintain tactile senses<br>Provision of musical instruments and music selection to counteract auditory |
| Social deprivation/lack of common areas | A communal area for dining and recreation (e.g., watch movies together), large enough to accommodate all crewmembers at the same time |

*Modified from NASA/SP-2010-3407.*

than being an observer. To increase the privacy related to personal distance in a restricted space, one strategy is to increase the time that a person needs to reach another one, for example with a complex pathway. However, care should be taken to ensure unimpeded egress in case of emergency. Acoustic and visual privacy could also increase the feeling of physical distance in small places.

Lack of privacy is an interpersonal stressor common in confined and isolated environments, which can lead to social illness and conflict (Ashcraft and Scheflen, 1976). Lack of privacy is a challenge that "astronauts have to adapt to in order to maintain a high level of individual and crew efficiency" (Kanas and Manzey, 2008, p. 16). However, on long-duration mission adaptation is not a suitable solution. Allowing astronauts to have a personal space that is sound-proof, has visual separation, and allows some physical distance would help them relax and take some time for themselves.

Finally, it is important to point out that the need for privacy can be strongly influenced by culture. Western astronauts, in particular, need to be alone for a set amount of time, whereas in other cultures people who prefer to be alone are regarded with suspicion or are seen as being deviant and nonconforming to group norms (Raybeck, 1991).

### 15.1.4.2 PROXEMICS

Proxemics is a habitability factor related to interpersonal space and to the perception of levels of intimacy and privacy within that space that influence elements such as territoriality and communication (Fig. 15.1.2). This factor is determined differently in diverse cultures (Hall, 1966).

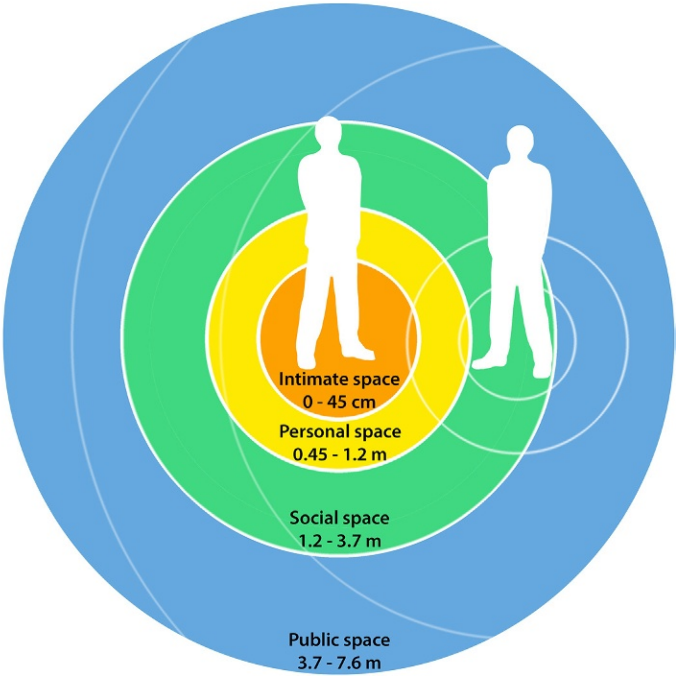

**FIG. 15.1.2**

Diagram representing the Hall theory on personal space limits.

*Courtesy: Webmaster.*

In microgravity, the human interaction with space is three dimensional and movement is achieved mainly with the upper part of the body instead of the lower limbs as on Earth (Gamba et al., 2000). For identifying up and down in this three-dimensional space, the polarity of the subject's internal reference has a stronger effect than the polarity of the visual scene (Glasauer and Mittelstaedt, 1998), in the sense that the main up and down reference is given by one's personal orientation and not by the surrounding space. However, when communicating with a person who is in a reverse position, it is difficult to perceive the facial movements and they need to turn in order to communicate. But who should be turning? In space, microgravity creates social interaction issues affecting proxemics. To better explain how proxemics works in space, consider the dinner on ISS. The astronauts use the orientation of the dinner table as their up and down reference; however, because there is no sufficient room around the table, one astronaut is floating above. Because of his peculiar position, he has difficulty communicating and interacting the rest of the crew (see Fig. 15.1.3).

**FIG. 15.1.3**

Astronauts eating inside the ISS Zvezda module.

*Courtesy: NASA.*

In conclusion, proxemics is the branch of knowledge that investigates the amount of space that people feel it necessary to set between themselves and others. In the design of the space habitat, due consideration should be given to this aspect of nonverbal human interaction and communication.

## 15.1.5 VARIETY AND VARIABILITY

Important aspects to be taken into account in designing a habitat are variety and variability. “In response to environment, people expect all of their senses to be moderately stimulated all the times. This is what happens in nature, and it relates not only to color and changing degrees of brightness, but to variation in temperature and sound. The unnatural condition is one that is static, boring, tedious und unchanging. Variety is indeed the spice–and needed substance–of life" (Birren 1983).

Humans have evolved on Earth to live on Earth. The consolation we get from the "home planet" strongly affects our psychophysiological stability. Wind, seasonally change of colors, light variation, day cycle, fragrances, temperature changes, and unplanned environmental events such as rain are part of the earthly reality in which humans have evolved. Those stimuli are part of the natural condition of human life.

The stimulation of variability is one of the elements that tend to be overlooked when designing an artificial environment, and its impact on human performance is often underestimated. "Variation is a fundamental characteristic to stimulate the human performance. Normal consciousness, perception and thought can be maintained only in a constantly changing environment. When there is no change, a state of 'sensory deprivation' occurs; the capacity of adults to concentrate deteriorates, attention fluctuates and lapses, and normal perception fades" (M.D. Vernon quoted in Birren 1982). Sensory deprivation, understimulation, or, sensory monotony is one of the key issues of long-duration space missions (Manzey personal communication, 2010). "Persons subject to under-stimulation showed symptoms of restless, excessive emotional response, difficulty in concentration, irritation, and in some cases, a variety of more extreme reactions" (Mahnke and Mahnke 1987). However, we must consider that "under-stimulated environment is as unacceptable as the overstimulated one."

"Terrestrial designs feature variety, but a variety which flows from a theme. Individuals experiencing this theme also have the opportunity of experiencing other themes in the course of a day. In space the number of designs must be limited. We need to ascertain what constitutes acceptable versus unacceptable variety in this closed environment" (Connors et al., 1985). In terms of temporal and spatial change, "stimuli arouse attention through the ability to increase the perceiver's level of complexity" (Dember and Earl 1957). "[This] is evidence that people prefer greater environmental complexity with time" (Dember and Earl 1957, after Connors et al., 1985). "If so, we should plan for increasingly complex arrangements as spaceflight lengthens" (Connors et al., 1985). Alternatively, we should assure a flexible arrangement that allows the astronauts to adjust and personalize the space according to the needs.

The concept of unity, complexity, and balance requires constant change and variability. This "balance" may be achieved by studying the harmony, contrast, and affective value of the systems elements (Mahnke and Mahnke, 1987) in relation to environmental design. Complexity may lead to confusion, while unity may lead to tedium: "We demand the play of opposite forces" (Ellinger, 1963).

The JAXA astronaut Naoko Yamazaki, after 15 days in space on Shuttle mission STS-131, described the return to the natural Earth environment in this way: On "re-entry and landing, when I stood on the ground, I was filled with emotion about how great it was to be back on Earth again. I felt Earth's nature all around me. The relaxing sensation of the wind on my face made me feel so grateful to nature" (Nishiura, 2010). With those simple words, Yamazaki captured the immediate perception of richness, variety, and beauty of the Earth natural environment by someone who has been constrained in a completely artificial condition, Indeed, the environment plays a fundamental role in terrestrial life: "Human beings receive 80 percent of their information from the environment" (Mahnke, 1996). "Nervousness, headaches, lack of concentration, inefficiency, bad moods, visual disturbances, anxiety, and stress usually are blamed on everything except a guilty environment, which may often be the root cause" (Mahnke, 1996).

## 15.1.6 LIGHT, COLORS, AND DECOR

The environment has a strong influence on human well-being and there are several factors to consider when developing an interior architecture. However, light and color importance is not limited to providing adequate illumination and a pleasant visual environment, but "they have great impact on our psychological reactions and physiological well-being" (Mahnke, 1996). "During the last two decades, it became increasingly clear that sunlight has profound effects on the human organism" (Mahnke and Mahnke, 1987). Natural light is of vital importance for humans as Mahnke explains, "all life on Earth is determined by the radiation of the sun" (Mahnke, 1996). On the ISS, psychological countermeasures to monotony, isolation, and behavioral health issues include "increased on-board music and lighting" (Kanas and Manzey 2008, p.193).

Light and colors have not only effects on human behavior and psychology but they cause also physical reactions. "Through our evolutionary development as a species we have inherited reactions to colour that we cannot control, …explain and … escape [from]" (Mahnke, 1996). "We are immediately, instinctively and emotionally moved… as soon as we perceive the color" (Beer, 1992). Besides psychological reactions and effects on vision and colors, there are numerous health-related biological effects. For example, the "light received through the eyes stimulates the pineal and pituitary glands. These glands control the endocrine systems that regulate the production and release of hormones controlling body chemistry" (Ott, 1985).

"Russian investigators have looked at the visual environment of a spacecraft and have proposed ways that changes in decor could be employed not only to relieve visual monotony but to maintain the space traveler's link to the home planet" (Petrov, 1975; cited after Connors et al., 1985). Natural plants have been proposed before as interior décor for the space station for their beneficial psychological effects (Bates and Marquit, 2010).

The impact of bad interior décor on habitability has been reported in the literature. "Skylab astronauts reported that the sameness of colours within their vehicle was disturbing" (Berry, 1973, after Connors et al., 1985). The spacecraft décor should be flexible to change and support visual variety. The International Space Station program clearly identified in SSP 50008 on interior color scheme the importance of avoiding boredom with color variety and flexibility:

- "Variety: Extreme simplicity can be carried too far. Drab, singular color or completely neutral (e.g., all gray) colour schemes and smooth, untextured surfaces are monotonous and lead to boredom and eventual irritation with the bland quality of the visual environment. The best interior design schemes are a balance of variety and simplicity" (SSP 50008, 1999).

- "Flexibility: Ease of changing decor should be considered. Decor might be changed during long missions, as crews are replaced during normal rotation, or when the space module needs to be refurbished. Plans for such change or rehabilitation should be included in the initial design so that changes can be accomplished with minimum effort, time, cost, and interference with ongoing operations. As an example, techniques for quick removal and replacement of wall and ceiling structural coverings should be considered to vary color schemes as well as replace worn or damaged coverings" (SSP 50008, 1999).

However, despite the promising guidance only in the Russian segment of ISS there is a real color variety, but there is no flexibility. Moreover, the current situation in the ISS is far from offering any perceivable wall décor, as walls, ceiling, and floor are covered with instruments that contribute to the visual chaos.

## 15.2 GENERAL HABITAT DESIGN

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Being the space natural environment of radiation, vacuum, temperature extremes and micrometeorites incompatible with human life, the first step in designing a space habitat is to isolate the astronauts from the external environment, and to create an artificial environment that supports human life (air, pressurization, temperature, humidity control, lighting, etc.), while limiting disturbances such as vibrations and noise. The next step in habitat design is to make provision for storage and processing of essential supplies (food, water, clothes, etc.), and for waste management. Finally, the habitat design will include operational aids (mobility aids, Velcro patches, etc.), and those elements and features that support quality of life and physical fitness, such as private sleeping quarters, equipment for physical exercise, flexibility, and personalization of the interior. Of particular importance are noise control and radiation shielding, which are discussed in dedicated sections of this chapter.

In this section, we will discuss the basic architectural elements of space habitat design.

### 15.2.1 HABITABLE VOLUME

Historical space habitats are an important source of data and lessons learned for the design of future space mission habitat. However, we should keep into account possible new constraints. For example, Skylab and the International Space Station (ISS) can be used as long-duration spaceflight precedents, but since the design of those stations was not volume constrained (they were assembled incrementally on orbit using elements launched separately), they are not good examples of minimum volume requirements for a spacecraft on a mission to Mars (NASA, 2014).

A pressurized volume is not equivalent to a habitable volume, or to Net Habitable Volume (NHV), which depends on "constraints on spacecraft shape, equipment, and layout of areas" (NASA, 2014). The pressurized volume is the total volume within the pressurized structure. The habitable volume is the volume remaining within the pressurized volume after accounting for all installed hardware and systems. The Net Habitable Volume is defined as "…the volume left available to the crew after accounting for the loss of volume due to deployed equipment, stowage, trash, and any other structural inefficiencies and gaps (nooks and crannies) that decrease the functional volume" (NASA, 2014). Fig. 15.2.1 shows the pressurized volumes of spacecraft flown until now.

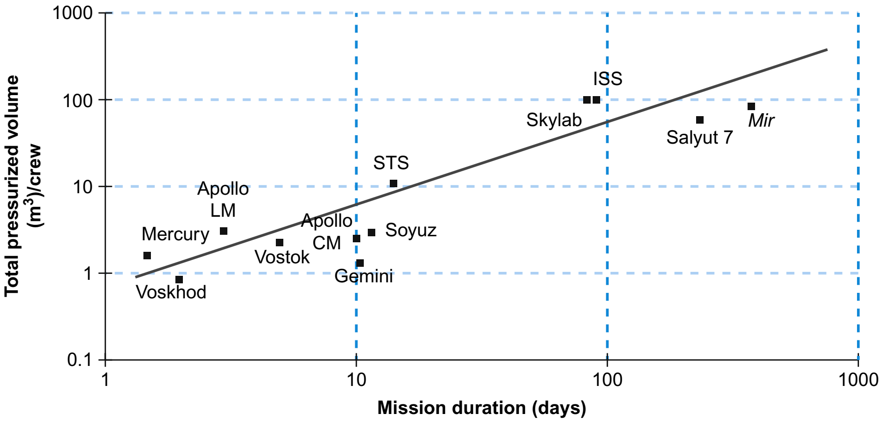

**FIG. 15.2.1**

Historical spacecraft pressurized volume.

*From NASA/SP-2010-3407 REV1, 2014. Human Integration Design Handbook.*

The NHV is variable. For example, on the ISS the NHV decreases significantly with the arrival of new cargo or in the European module (Columbus) when the large MARES (Muscle Atrophy Research and Exercise System), normally stowed in a dedicated rack, is deployed in the aisle. Fig. 15.2.2 shows MARES and cargo bags temporarily stowed in the end cone of Columbus.

To estimate the minimum habitable volume needed per crew member in m$^3$ as function of mission duration, the following formula can be used (NASA, 2014):

$$\text{volume / crewmember} = 6.67 \times \text{Ln}(\text{duration in days}) - 7.79 \qquad (15.2.1)$$

This gives a habitable volume of 26.85 m$^3$ per crewmember on 180-day mission duration, and a total volume of 161 m$^3$ for a crew of six. In comparison, the ISS has a larger habitable volume. The ISS has a total pressurized volume of 837 m$^3$. We know that Node 2, one of the ISS modules, has a pressurized volume of 79.4 m$^3$ and a habitable volume of 25.8 m$^3$, equal to 32.5% of the pressurized volume. Assuming that the same proportion applies to entire ISS, the overall habitable volume of the station is 279 m$^3$.

To calculate the required volume, it is necessary to consider that a spacecraft habitat has to accommodate mission-specific tasks and all what is needed to satisfy basic human needs of eating, sleeping, exercising, and personal hygiene. Exercising

**FIG. 15.2.2**

European Space Agency (ESA) astronaut Tim Peake operating the Muscle Atrophy Research and Exercise System (MARES) equipment in the Columbus module. In the background, several large cargo bags *(white)* are stored in the module end cone.

*Courtesy: NASA.*

is critical to maintain health in a microgravity environment and requires extended use of equipment. The total volume will be subdivided and allocated in accordance with criteria of efficiency and functionality. Appendix A provides historical data on volumetric dimensions per activity on some spacecraft and on analog ground systems. Detailed layout and ECLSS (Environmental, Control and Life Support System) parameters must take into factors related to health, safety, privacy, and comfort/performance (e.g., temperature and humidity).

Different considerations apply to the sizing of Moon and Mars habitats (not covered in this book), because moving in partial gravity is different from floating in microgravity (e.g., jumping on the Moon) and takes place on a bidimensional surface as on Earth.

## 15.2.2 VISUAL PERCEPTION AND ORIENTATION

Among the senses, vision is the most important one for perceiving external reality. Indeed 80% of the sensorial information about the world is of a visual kind (Mahnke and Mahnke, 1987; NASA, 1995, 2014; Kosslyn et al., 1995; Romanello, 2002). In microgravity, visual perception becomes even more important because “astronauts rely on the visual sense to perform every aspect of their missions, including reading text, scanning instruments, observing their environment, executing tasks, and communicating with other crewmembers” (NASA, 2014).

In space, human vision is affected by many factors. In microgravity, because of neutral posture, the angle of sight is tilted downward of about 24 degrees. On

**FIG. 15.2.3**

Tom Marshburn performs a tonometry eye exam on Chris Hadfield to measure intraocular eye pressure.

*Courtesy: NASA.*

the Moon or Mars such tilting is less because of partial gravity. Color perception is also modified. In particular, it has been observed that a "general decrease in brightness-sensitivity became evident" (Schlacht and Birke, 2011). Microgravity causes also visual alterations. Since early human spaceflight NASA has been concerned about astronauts' visual acuity impairment, but for many years reported visual changes were considered minor and temporary. In 2012, it was found that 15 male astronauts had experienced visual and anatomical changes of the eyes during or after long-duration flights on ISS. The anatomical changes were serious. The syndrome, known as VIIP (Visual Impairment and Intracranial Pressure), seems related to volume changes in the clear fluid that is found around the brain and spinal cord. However, studies and investigations are still ongoing (see Fig. 15.2.3). Visual impairment is not only a serious postflight medical problem but also a threat to astronauts' performance on long-duration missions, in particular to Mars (Space Safety Magazine, 2017).

Experiments conducted on the ISS have shown that after several months on orbit the visual perception of objects height, depth, and distances is altered. In particular, experiments consisting of estimating the dimension of a cube have shown that astronauts tend to underestimate the depth and overestimated the height. Conversely when drawing a cube the astronauts tend to make height shorter and depth longer. Astronauts tend also to underestimate the distances of objects located either at very close range (<60 cm) or at long-range (180 and 1500 m). "The increase in perceived height of the cube and the underestimation of its distance are inconsistent with the visual size constancy rule, which predicts that we tend to attribute a smaller size to an object when we underestimate its distance" (Clément et al., 2013). Visual perception modifications are among the main factors to be considered for habitat design. Those related to normal conditions, as well as those changes in the visual field related to fatigue (Rötting, 2001). Misperception of object distance may have serious safety consequences, in particular when manual operation is involved like the use of a robotic arm. In 1997, misperception of distance and speed during manual docking operation caused a Progress cargo ship to collide with the Mir space station, causing a serious emergency and lasting damages.

Orientation in microgravity is primarily based on visual perception because "people suppress vestibular signals and become increasingly dependent on vision to perceive motion and orientation" (Mallowe, 2001). In floating conditions, the interaction with the habitat is tridimensional. In comparison with 2D walking on Earth surface, 3D floating in space makes the entire interior volume usable. There is no up and down, no floor nor ceiling. The interior colors on ISS are used primarily to help orientation (SSP 50008, 1999). In a study on orientation comparing two segments without equipment, the colors used in the Russian segment turned out to be more effective than the layout approach used in the American segment to build the up and down references (Schlacht et al., 2009). Based on the heritage from Mir space station, the Russian used a color scheme that relates to the Earth natural environment, using green, tan, and brown of lighter color for the "up" location, and deeper color for the "down" location. In the American segment orientation is largely provided through architectural features (position of lights, asymmetric shape of hatches), which are somehow lost when equipment and research facilities are installed (see Fig. 15.2.4).

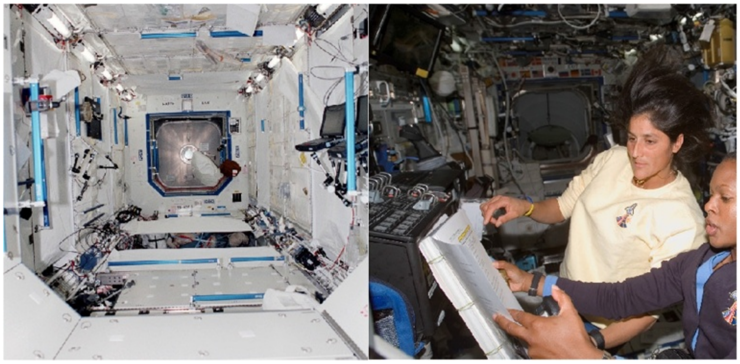

**FIG. 15.2.4**

On the left Destiny Lab's interior as it appeared when it was added to the ISS in 2001. The asymmetric shape of hatches and the position of lighting provide clues for orientation. On the right, the Destiny Lab after installation of research equipment, the clues are no longer clearly visible.

*Courtesy: NASA.*

## 15.2.3 POSTURE AND MOBILITY

The space habitat design must consider the gravity environment. Table 15.2.1 summarizes the gravity environment of orbital and exploration missions compared with Earth.

Reference to ground, microgravity allows greater use of floor and ceiling. In microgravity astronauts translate using their arms and hands, and by pushing off surfaces with their feet.

On orbit there is no difference between standing up and lying down. When astronauts stand still, e.g., when they are at a workstation, relaxing, or sleeping, they assume roughly the same position of when floating in water, with the arms somewhat raised out in front. This position, similar to the fetal position, is called neutral body posture. The position is automatically assumed when the muscles relax because “there is the least tension or pressure on nerves, tendons, muscles and bones” (University of Connecticut, 2011).

Comparing with normal sitting or upright earthly posture, the neutral body posture “generates a distorted relationship among the bodily geometry, such as between the expected position of the hands and sight line as in the case of the use of a laptop computer” (Masali, 2010a). In particular, “the sight line drops 25–30 degrees down with respect to the Ohr-Augen-Ebene (OAE) or Frankfurt Horizontal Plane” (Masali, 2010b). On Earth, “we look about five meters away on the ground to see way ahead and, maybe, obstacles and perils” (Masali, 2010b). The sight drops in microgravity and “in an evolutionary frame this means an extraordinary conflict with the rotation of the basicranium and the increasing of the occipital surface” (Masali, 2010b). Fig. 15.2.5 shows the “standard” Neutral Body Posture (NBP) used at NASA for the design of workstations and tools.

NASA discovered the neutral body posture from photos taken on board the early space station Skylab while the astronauts physically relaxed. “Since Skylab, NASA has significantly built on its human posture research. For one, a Space Shuttle study demonstrated that there is a range of NBPs for individuals. In another posture study, researchers found the spines of astronauts lengthened in zero gravity on the International Space Station (ISS), information that has since influenced the size and design of the recently-developed Orion Multi Purpose Crew Vehicle. Lastly, NASA has future plans to perform a new study on the changes that occur to body shape, size, and NBP onboard the ISS” (NASA Spinoff, 2013).

**Table 15.2.1** Gravity environment for orbital and exploration missions

| Environment | Gravity (g) |
|---|---|
| Earth | 1 |
| Mars | 0.38 |
| Moon | 0.16 |
| Orbit | $10^{-5}$–$10^{-6}$ |

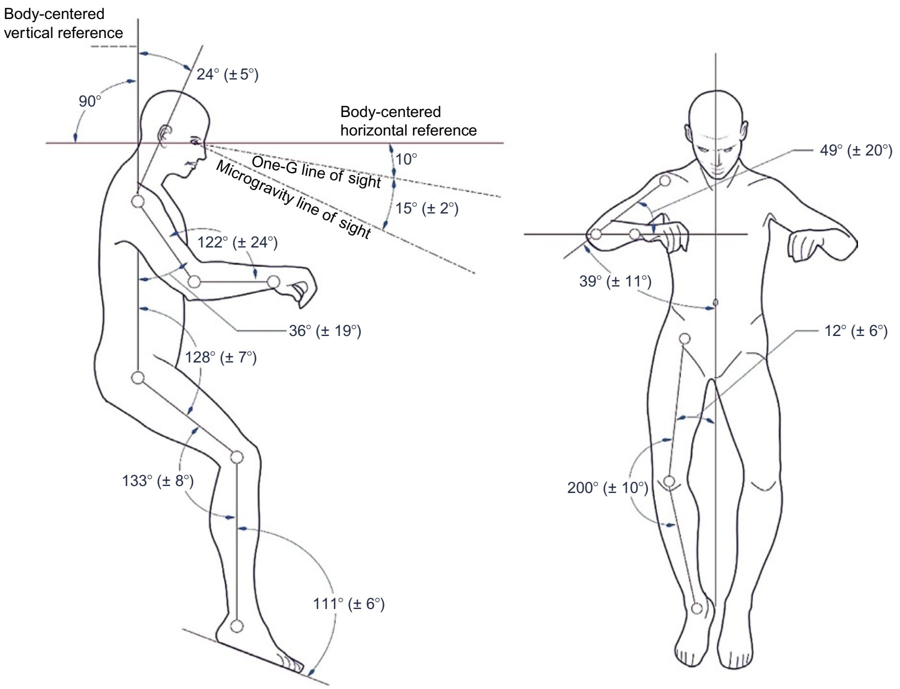

**FIG. 15.2.5**

The standard neutral body posture (NASA/SP-2010-3407) was derived from photos of 12 astronauts taken onboard Skylab.

"The neutral posture adopted by humans in space offers a range of new body movements, gestures as well as repositioning of the body in unexpected manners defining a different workspace envelope. It is therefore necessary to identify the new postural parameters, postural coordinates and their relationship within the man-object interface (ergonomic approach) as well as the interpersonal relationship of those working together in zero gravity field (proxemic approach)" (Masali et al., 2010).

On Earth we stand, walk or run, in weightlessness the human motion is completely different. In microgravity, you are floating. In order to move, at first you need to grab something fixed and then push yourself and "fly." Handrails are provided for that purpose. if you are not able to grab something fixed, the body reacts instinctively by trying to swim, but as there is no water around you and therefore no drag to "push" against, no matter how much you move, you will stay in the same place. Table 15.2.2 shows the typical astronaut motions in microgravity.

Movement influences the distance with other crew members, affecting proxemics relations and involving sociocultural factors (Masali et al., 2010).

Moving around in microgravity is not easy and it is even more difficult if you think of the crowded ISS environment where there are instruments, equipment, and cables

**Table 15.2.2** Characteristic astronaut motions in microgravity (Newman, 2000)

| Characteristic motion | Description |
|---|---|
| Landing | Flying across module and landing |
| Push off | Pushing off and flying |
| Flexion/extension | Flexing or extending limb |
| Single support | Using one limb for support |
| Double support | Using two limbs for support |
| Twisting | Twisting body motion |
| Reorienting | Usually small corrections for posture control |

everywhere. ISS astronaut Ed Lu describes his approach as follows. “My technique for flying is a little different. Instead of flying headfirst like Superman, which requires that you first rotate your body so that it is pointing where you want to go, I find that it is easiest to simply launch yourself in whatever direction your body is aligned. Then I use a hand to …rebound off the wall or ceiling while changing my direction, then again rebound off the next surface with my feet. I like to do flips and spins when I fly around now” (Lu, 2003).

#### 15.2.3.1 FOOT RESTRAINT

As mentioned, moving is not easy in weightlessness but also standing still is difficult. It involves a completely different effort and approach than on Earth. Restraints are needed to prevent floating.

The first designs to restrain the astronaut in a standing still position were developed for Skylab, the first US space station.

Skylab's floor and ceiling consisted of grids of equilateral triangle cutouts machined from aluminum plates. The grids served as both a handhold and a locking surface for special shoes. The sole of each shoe was fitted with a triangular aluminum cleat shaped to allow engagement/disengagement in the triangular cutouts by giving a twist. The system allowed the astronaut to restrain himself into position wherever he wanted. To use the system, the astronauts needed to always wear specific shoes. Fig. 15.2.6 shows the triangular cleat on the shoe sole inserted into the cutout.

For Spacelab, the habitable module installed in the cargo bay of the Shuttle for microgravity research missions, it was decided to have solid walls, ceiling, and floor (although such terms are freely exchangeable in a microgravity environment) to reduce the noise generated by air circulation fans. There were two primary restraint features on Spacelab: cloth foot loops, and hand holds. The latter were also used for moving around. Initially an astronaut would tend to prefer hand holds as restraint and then more and more foot loops as he learned to use them. However, it was observed that often foot loops were not used as foreseen. Usually engaging one foot and using the other one in various ways as support, for example to “push backwards against

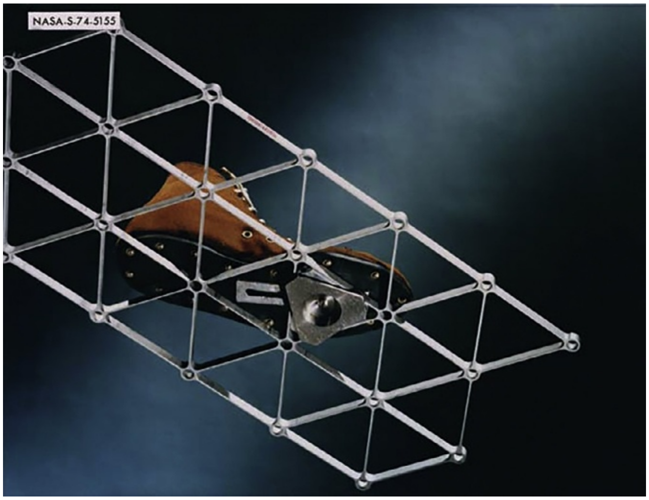

**FIG. 15.2.6**

Skylab foot restraint system.

*Courtesy: NASA.*

some structure forcing the crew member's foot further into the one foot loop being used" (Wichman, 1992). A study performed in 1992 by the Aerospace Psychology Laboratory of Claremont McKenna College in US, explained the reason why foot restraints were unused or misused. In Fig. 15.2.5, notice "that the angle between the shin bone and the sole of the foot is $111^0$, not the $90^0$ into which they are forced when standing in one- g. Thus, to keep one's foot in a cloth foot loop it is necessary to contract the muscles (primarily the tibialis anterior) overlying the shin to raise the foot $21^0$ and then hold that contraction. Astronauts have told us that this is an uncomfortable thing to do" (Wichman, 1992).

On the International Space Station, there are currently adjustable foot restraint for short- and long-duration operation. The Long-Duration Foot Restraint (see Fig. 15.2.7B) is designed to provide a more adjustable and comfortable positioning for crew to be able to work for longer periods of time. It can be placed at any height in front of the workstation. The foot plates clip onto double bars at any distance apart. The double bars can rotate to provide multiple angles.

On the ISS, astronauts wear shoes only when exercising on the ISS treadmill or bicycle; otherwise, they just wear socks (or nothing). When they come back to Earth the bottom of their feet has no calluses, but often they develop calluses on the top of their feet, near the toes. This is caused by frequently wedging their toes in foot restraints and handrails. Astronaut Kelly, who spent 340 days in space, stated that "the top of my feet developed rough alligator skin because I used the top of my feet to get around here on the space station when using foot rails" (Chan, 2016).

**FIG. 15.2.7**

In (A) astronaut Daniel Bursch uses foot restraint while working the controls of the Space Station Remote Manipulator System (SSRMS) (2002). The insert (B) shows details of the ISS adjustable foot restraint for long-duration operations. In (C) astronaut Edward Lu works using a "wrapped" handrail as foot restraint (2003).

*Courtesy: NASA.*

### 15.2.3.2 HANDRAILS

On the International Space Station handrails are used in combination with seat track. A seat track is an aluminum interface usually bolted to the floor of airplanes, and shaped with channel and dots such to allow configuration changes of spacing between passenger seats. The inside of the Space Station is composed of many replaceable and interchangeable racks for experiments and system hardware. Each rack has seat tracks on both sides facing the crew. Seat tracks are used to place brackets to support equipment like laptops and cameras, and in particular handrails.

Handrails are used for helping the crew with their mobility around the station as well as keeping them stationary when desired. They are designed for hand use, but astronauts also use them as temporary foot restraint. ISS handrails come in different lengths. There are two types of handrails on ISS. The original type of handrail was designed in accordance with the (usual) one-handed operation requirement that "nonfixed handles shall be capable of being placed in the use position by one hand and shall be capable of being removed or stowed with one hand" (NASA-STD-3000). The newer version violates the one-hand requirement (two hands are needed for installation) but is much less expensive to produce due to the fewer number of moving parts. Fig. 15.2.8 shows ISS handrail and seat track.

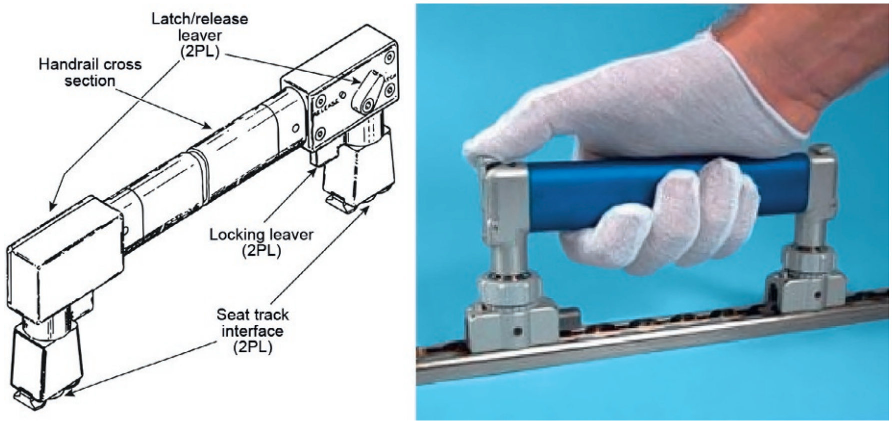

**FIG. 15.2.8**

Removable handrail and seat track (NASA, 2014, SSP 57020).

## 15.2.4 EATING

Food and drink on space missions must not cause health or hygiene problems. They should be easy to swallow and digest, and also to prepare and consume (NASA, 2000). The Food Systems Engineering Facility (FSEF) at NASA Johnson Space Center takes care of nutritional values, sensory impression (flavor), preservation, and stockage. Other relevant challenges are temperature, acceleration, vibration, and the limited volume available on orbit for storage.

On ISS, "the Russian Zvezda service module is used to prepare meals" (NASA, 2002). "During a typical meal in space, a meal tray is used to hold the food containers. The tray can be attached to an astronaut's lap by a strap or attached to a wall" (NASA, 1996). In microgravity, to hydrate the food and also to prevent that bit and pieces float away, water is added to make it sticky. For the same reason salt and pepper are available but only in a liquid form. The ready-made food is eaten with classical western cutlery made of metal or plastic three times per day, during breaks, lasting 1 h each (Voss, 2003).

"Astronauts will choose 28-day flight menus approximately six months pre-launch" (NASA, 1996). However, astronauts report different taste perception in microgravity and it is not uncommon that they dislike the meals they selected. With longer mission duration, it is more and more important that the food is "satisfying and delicious as well as nutritionally balanced" (NASA Vikie Klories quoted by Ferraris, 2004). One possibility is to add salt to make it tastier; however, there are side effects on bone loss, which is one of the most important effects of exposure to microgravity. Salt intake affects the acid balance of the body and bone metabolism. So, high salt intake increases acidity in the body, which can accelerate bone loss.

The water is recycled from the liquid of the urine and from the vapor of the breath and then warmed if necessary. "We humans exhale water vapor (breathe on a cold window to see that), and this water is condensed out of the air using something similar to an air conditioner. The water is then purified and we use it for drinking water" (Lu, 2003).

## 15.2.5 SLEEPING

Astronauts sleep in sleeping bags, which “they just attach to a wall or floor or ceiling to sleep” (Dennis Dillman communication 1997, in NASA, 2011a). Inside the ISS, they can sleep in the two-person crew quarters with a window in the Zvezda Service Module (Dismukes, 2003) or in the sleeping station, which is “only used on flights where the crew is working around the clock in two shifts”. In addition, “there are some astronauts who just like to sleep floating around” (Karina Shook communication, 1999, in NASA, 2011a).

Sleeping in space is not so simple and most of the astronauts are reported to sleep only for 6 of the 8 planned hours. It is well known that space missions affect the circadian rhythms, increasing sleep deficiency and the use of medication. Sleep problems have been reported by astronauts ever since the early days of space flight (NASA, 2011a): “You need to get used to the lack of touch on your back or on your side, because you are really floating in your bag, only lightly touched by the ties holding you down. Thus, the feeling of tired heaviness which makes you “hit the sack” and feel sleepy in bed, is absent, and some astronauts cannot really get used to that. …Every time that I got into it and closed my eyes I feel like falling. Now I have learned that I string out my sleeping bags like a hammock and make it as tight as I can and then I get in it and zip it up and use those Velcro® straps and make it as tight as I can. I need to feel like I am tied down to something touching something, or I feel like I am falling and it will wake me up” (NASA, 2001).

Rarely there are astronauts who love to sleep in space: “It's just lovely sleeping in space, because you just instantly relax. There's no pressure in your shoulders and hips and it's just lovely” (Voss, 2003). Another problem is the noise from the fans that circulate the air; however, also in this circumstance, astronauts react differently: “[It] makes it easy to go to sleep, just like your fan at home” (Joe Tanner communication 1997, in NASA, 2011a).

Besides, “the excitement of being in space and motion sickness can disrupt an astronaut's sleep pattern” (Dismukes, 2003). When it is time to wake up, a shuttle crew receives wake-up music, which is selected each time by a different astronaut, whereas a space station crew uses an alarm clock (Dismukes, 2003).

In conclusion, most astronauts sleep for 6 h. Studies on sleep and circadian cycle have reported that after 7 days of 6 h of sleep, a person's performance is equal to that of a person who has not slept for 24–36 consecutive hours. Lack of sleep slows the mental processes and compromises reasoning ability and memory, with worrying consequences upon the crewmembers' return and upon the efficiency and therefore the safety of the mission (Monk, 1996).

## 15.2.6 PERSONAL HYGIENE

Microgravity “makes going to the bathroom rather difficult” (Dennis Dillman communication 1997, in NASA, 2011a), and in the early times of human spaceflight there was not even a bathroom. However, Mercury missions were short duration; therefore the problem was limited, but during Gemini the crew of two had to inhabit the tiny capsule for 2 weeks. "This meant that the two pilots would not only work together in much the same way that airliner pilots and copilots work together, but they would have to perform all of their life activities for two weeks while seated virtually shoulder to shoulder. There could be no showers, toilets, nor wash basins. There would be no kitchen, dining room, nor bedrooms" (Wichman, 1992).

Toilets on Skylab and Shuttle worked on similar principles as the two currently on ISS. The ISS toilet is composed of a small cabin with the Waste Collect System (WCS), a multifunctional system used to collect, recycle, or process biological wastes (Thomas and Oliveaux, 1999).

"The toilet is operated by air pressure. A fan does the work that gravity does on the ground. Urine is sucked inside the toilet and is collected in a 20-liter container. When these are full they are discarded in the *Progress*. For collecting solid waste the toilet has plastic bags you place inside, and air is sucked through tiny holes in the bag. Everything gets collected in the bag (hopefully) and the bags self-close with an elastic string around the opening. You then push the closed bag through a hole into an aluminum container, and put a new bag in place for the next person" (Lu, 2003). The Russian cargo vehicles Progress is the primary method of eliminating trash and waste from the ISS. The total volume available for trash/waste disposal is on Progress is 5.8 $m^3$. On its way back from ISS, the Progress cargo vehicle burns and disintegrates in the upper layers of the atmosphere (SSP 50841, 2000).

Technically, the WCS includes two foot restraints and two body restraints to position and hold yourself on the seat for solid biological wastes. For urine, the astronaut uses a personal funnel attached to a hose, and the funnel is differently shaped for women and men (Thomas and Oliveaux, 1999).

The toilet cabin is also used by the astronauts to wash, shave, cut their hair, and maybe change. When they wash or shave, they need to take care not to disperse water drops or hair in the air. To suck up all the hair, they use a vacuum cleaner hose. Astronauts wash themselves with wet wipes soaked in body cleaning solution mixed with warm water and a dry shampoo. Because the solution and dry shampoo do not need rinsing, the astronauts use four liters of water for personal hygiene instead of fifty liters used on Earth (Thomas and Oliveaux, 1999). "We don't have a shower up here (the water wouldn't go down through the drain anyhow), so we wash using no-rinse soap and shampoo and a towel. It is the same stuff they use in hospitals for bedridden patients, and it works really well. That being said I am looking forward to a long hot shower when I get home" (Lu, 2003).

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## 15.3 HABITAT DESIGN—SPECIAL TOPIC: NOISE CONTROL

**Jerry R. Goodman, Ferdinand W. Grosveld, Christopher S. Allen**

### 15.3.1 INTRODUCTION

The acoustics environment during space operations is characterized in Chapter 4, in the Acoustics section of Space Flight Environment. Limiting the acoustic exposure levels in the crew compartment and habitat to the defined requirements is deemed essential to achieve a safe, functional, effective, and comfortable acoustic environment for the crew.

A noise control plan is required to define and lay out the plans and efforts necessary to achieve compliance with the acoustic requirements. The status and progress of the noise control plan needs to be actively monitored to ensure effective communications on efforts to limit noise, identify any areas of emphasis and concerns early in the design process, and allow timely remedial actions to preclude unnecessary impacts. Detailed discussions of the noise control plan and its major components are presented, followed by various applications of successful noise control design in habitable space environments.

### 15.3.2 NOISE CONTROL PLAN

A noise control plan is a document that defines the efforts necessary to meet established requirements. The noise control plan, at a minimum, should include:

- The overall noise control strategy
- The supporting acoustic analysis approach
- The testing and verification procedures for the system and hardware components.

More detailed considerations that should be included in the plan are discussed in Goodman and Grosveld (2015).

#### 15.3.2.1 NOISE CONTROL STRATEGY

A sound source radiates energy that is perceived at the receiver location as a pressure deviation from the local ambient pressure. The source is characterized by the sound energy per unit time, or sound power, and the pressure deviations at the receiver are measured as sound pressure levels. The sound energy emitted from the source follows various paths into the crew compartment. Noise control is the application of designs and technologies limiting the noise at the source and along its path to achieve acceptable levels at receiver locations. The acceptability of the resultant acoustic levels at the crew receiver locations is defined by the requirements for the habitable environment. It is very important that noise control be incorporated at the earliest possible time in the design and development cycle, when required changes and more design options can be incorporated with minimal design and program impacts.

### 15.3.2.1.1 Noise Sources

It is important to identify and control noise sources, as they provide acoustic energy to the crew compartment or habitat of a spacecraft. Sources need to be classified as to whether they are continuous or intermittent because environmental limits in space operations are specified in this manner. Fans, pumps, motors, and compressors in the Environmental Control System (ECS) or Thermal Control Systems (TCS) of the spacecraft are usually the dominant continuous noise sources. Special considerations should be given to the design, procurement, and noise control of such hardware. Such hardware needs to have limits established for them—limits that can be controlled and are consistent with achieving compliance with the established habitable volume requirements. An excellent example of the significant benefits of controlling fan noise is provided later, in discussions of the Russian "quiet fan" used in International Space Station (ISS).

There are two basic options to controlling the noise emitted by a source:

- Select or develop noise sources that are quiet by design, while considering acoustic emission as well as other characteristics in the choice of this hardware; or
- Focus on development activities to quiet the selected design or hardware to the extent required.

Sound sources should be characterized by their sound power output level. This information is provided by either the designer or the supplier, and measured in accordance to applicable international standards (ISO, 2003). It is important that noise sources be tested and characterized to reflect their installed configuration in the system, their operational mode, and "loading" (e.g., at appropriate flow rates and back pressure) when installed into the flight configured system.

### 15.3.2.1.2 Noise Paths

Two basic sound propagation paths need to be addressed:

- Airborne
- Structure borne

Airborne sound comes from the inlets and exhausts of air ducts, directly from exposed equipment or closeouts, or from sound leaking through air passageways or gaps. This type of sound can be controlled using mufflers or silencers for broadband noise, resonators for narrow band noise, active acoustic control systems (e.g., inside the duct), applications of sound-absorbing materials (e.g., in the duct lining), and by the use of appropriate materials to seal the gaps or otherwise block the noise.

Structure-borne noise originates from a vibrating source or an impact event, and is transmitted by structural vibrations and the resultant energy transfer at mountings, connections, and from surfaces. This noise can be reduced by the use of vibration isolators, active vibration control systems, applications of passive or active damping materials, by the decoupling of lines to preclude the transfer of vibration, or by otherwise limiting the energy flow through the structure to radiating surfaces. The addition of vibration isolators to fans and pumps is an important design practice that should be used in noise control.

Enclosure radiated sound is that radiated from, or is transmitted through structural enclosures, panels, shelves, and other types of closeout materials, that is either airborne or structural borne noise, or a combination of them. This noise contribution can be lowered by structural or material changes, the addition of barrier or stiffening materials to reduce transmission, the addition of damping or viscoelastic materials to minimize radiation, addition of absorbent materials inside the enclosure to absorb acoustic energy, or through the use of active structural acoustic control.

#### 15.3.2.1.3 Noise at the Receiver Location

Acoustic requirements for the various types of limits to be met at the location of the receiver (the ear of a crewmember) were discussed in Chapter 4.2 on Acoustics in Chapter 4. The acoustic environment in the receiving space is affected by its volume, surface area, the dimensions relative to the acoustic wavelength, the ratio of the dimensions, the reverberation time, and the absorption properties of the crew compartment. At higher frequencies, where the sound pressure in the reverberant field can be assumed constant, the noise in the receiving space is best controlled by increasing the absorption coefficient of the bounding surface areas.

The application of these absorption materials to the interior surfaces of the crew habitat can be limited in use because of flammability, outgassing, lack of wear and tear resistance, and other harmful properties of the material. Although porous acoustic materials often have good sound-absorbing properties, they may not be suitable for use within the crew compartment if they either particulate, or collect moisture, dirt or other contaminants detrimental to the health and wellbeing of the inhabitants. If their use is necessary, these materials need to be covered or contained such that the concerns are remedied, while good absorption properties are maintained.

At the lower frequencies, a noise control strategy can be based on active acoustic control if the application can be made practical using reliable hardware and robust control software. The design should address redundancy and mitigation measures relating to a possible failure of the active control system. The acoustic environment in the crew compartment or habitat should be controlled at all potential receiver locations, or at the least at established crew operation positions, although it may be very difficult to estimate or control all future crew positions. At the crew receiver locations, other approaches for reducing the sound pressure levels or changing the effects of the factors described are limited. Options at the receiver are to enclose the receiver, move the receiver, or require that the receiver wears hearing protection. If the receiver acoustic levels are too high because the predicted or measured levels have been underestimated or not understood adequately, the remedial alternatives lead back to reducing emissions from the noise sources or along the paths to the receiver. This is all the more reason why early testing of the crew compartment with the basic systems installed should be performed to ensure problems can be found, quantified, and appropriate remedial actions implemented in a timely fashion. When this assessment is postponed until late in the flow schedule, any noncompliance discovered at that time will more severely impact the design and delivery schedules. Remedial action then will prove to be more difficult, costly, and design change options more limited. The noise control plan and design flow schedules should include time for this valuable effort, and should be conducted as early in the program as possible.

The option of moving the receiver is practical only if the crew can be relocated to areas not affected by the higher noise levels. By providing separate sleeping quarters, the crew can be isolated from noise that otherwise would disturb their rest or sleep cycles. Controlling the noise directly at the ear of the receiver usually is not acceptable because the levels would be tolerable only with the use of hearing protection, which presents significant physiological and operational concerns. Exceptions can be made for short duration events such as cabin depressurization, the launch sequence, or some segments during the descent of the space vehicle.

#### 15.3.2.2 ACOUSTIC ANALYSIS

An acoustic analysis is an important part of the noise control plan because its predictions provide an estimate for the resultant noise levels in the crew compartment habitat throughout the design phase. The acoustic analysis should be based on a semiempirical approach, in which possibly inaccurate assumptions, calculations, and procedures in the analysis can be replaced by validated test results. The analyses should be performed at the component or assembly levels of the contributing sources, and along their paths to the receiver location. The purpose of the semiempirical acoustic analysis is to have a continuously updated and test correlated documented assessment of the acoustic environment as it relates to compliance with the requirements. This provides insight and understanding of the underlying acoustic principles, thus allowing efficient and effective noise control implementation.

The first step in estimating the noise environment is to quantify the sound power of the noise sources to determine which measures need to be implemented along the pathways to the receiver location, and to establish priorities for noise control efforts. Analysis and testing should be maximized to provide updated information on source, path, and receiver information. Breadboard testing or piggyback testing on major noise source subsystems should be used to expose acoustic effects, and the actual noise levels should be used to update the analysis.

A variety of tools are available for the acoustic analyses, each of which has advantages and disadvantages depending on the frequency range of interest, the computational and financial resources available, the accuracy required, the type of source, the nature of the noise paths, and the characterization of the receiving space. Tools include the use of analytical formulas, geometric computer-aided design (CAD) models, statistical energy analysis (SEA) programs, finite element (FE) and boundary element (BE) analysis codes, acoustic ray tracing programs (Pilkinton and Denham, 2005), technical and mathematical computing languages, and the traditional programming languages.

#### 15.3.2.3 TESTING AND VERIFICATION

Sound power and directivity measurements of noise sources need to be performed, and the results should be used to determine possible quieting approaches. Simple mockups or prototypes can be employed to determine the effectiveness of mufflers or other noise reduction devices inexpensively. Testing of the designs and design approaches should be performed as much as possible prior to formal verification testing to minimize unforeseen results, provide time for remedial actions if required, and supply a basis for updating of the analysis to reflect test results. Acoustic measurements should be included in the breadboard testing of systems, like for example, the environmental and thermal control systems.

It is important to operate each equipment item individually to determine its noise contribution and frequency content relative to the total noise levels. This provides information for the ranking of the contributing sound sources in selected frequency bands, and helps establish priorities for the work to be done. Testing setup, conditions, instrumentation, procedures, and results should be included or referenced in the noise control plan and implemented accordingly. As noted previously, it is recommended to allow for testing early in the final checkout so that time is available for remedial action with minimized impacts. Verification is very important in that it defines how and what needs to be done to prove that the requirements have been met. Verification needs to address the testing, demonstrations, analysis, and the equipment and programs used in the verification process.

## 15.3.3 NOISE CONTROL DESIGN APPLICATIONS

The noise control plan should define the approaches to be used, and the efforts that can be made at the source, path, and receiver levels to control the noise for compliance with the established requirements. The Space Shuttle program used an approach in which all continuous noise sources were identified; the source to listener paths were determined; the combined systems noise in the flight deck and middeck were estimated; the contribution of each source relative to the total noise was established; and the applicable noise criteria were specified (Hill, 1992, 1994). The basic noise control approach used in the Space Shuttle Program is shown in Table 15.3.1 (Hill, 1992).

Typical noise paths aboard the Space Shuttle are shown in Fig. 15.3.1 (Hill, 1992).

In both the Space Shuttle and the ISS, the noise permitted in the habitable environment was controlled by budgeting allocations to the equipment sources and noise pathways. European modules for the ISS use a somewhat different approach. Budgets are established for the allowable sound power of hardware systems. The sound power contributions of these sources are then determined, and any necessary pathway reduction efforts using testing or a database of prior testing are implemented. The test results are used to ensure compliance (Destafanis and Marucchi-Chierro, 2002; Goodman and Grosveld, 2015).

The sound power present in the crew compartment is the result of the noise source power being channeled through the various radiation and transmission paths, while taking into account any insertion loss through panels and materials. The sound power at the receiver is then converted into sound pressure levels by using the room

**Table 15.3.1** Space Shuttle noise control

- **Systems engineering approach**
- **Identify all noise sources**
    - Part number, system, location
    - Continuous or intermittent
    - Relative significance (contribution to total crew module noise)
- **Determine source-to-listener noise paths**
    - Airborne
    - Enclosure transmission
    - Structure-borne
- **Estimate combined systems noise in flight deck and mid-deck**
- **Establish relative contribution of each source to total noise**
- **Specify noise criteria for each source (allowable)**
- **Define noise test requirements, components, system, general & adjacent working areas**
- **Identify components/system elements requiring noise control measures**
    - Perform analyses to establish dynamic behavior of suspect hardware (finite element methods) as required
    - Determine silencing required in each octave band
    - Evaluate available options (see silencing options)
    - Assess cost, weight, downtime, workaround
    - Optimize silencing modifications
- **Perform noise test(s) to verify effectiveness of noise mitigation applications**
    - Compare with allowable noise requirements
    - Noncompliance = reassessment/additional silencing

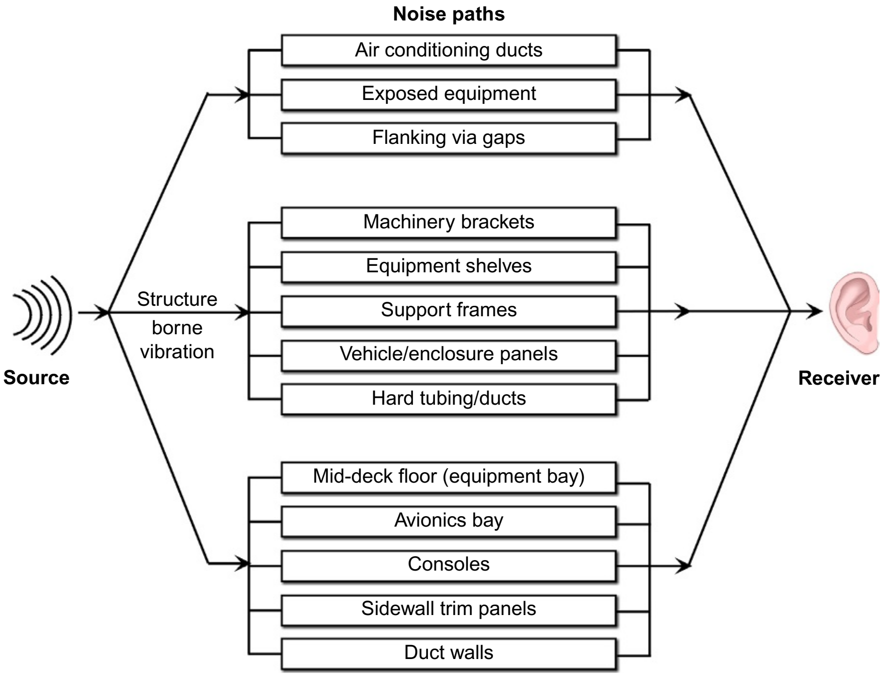


**FIG. 15.3.1**

Space Shuttle Orbiter noise paths.

equation and constants (Beranek, 1988). Although concentrating more on predictions than on the budgeting and control, the approach used for the ISS US Laboratory module, Destiny, similarly focused on the sound power and resultant effects of the design (Denham and Kidd, 1996). The ISS program also developed a good noise control plan for use with ISS payload racks as defined in Appendix H of SSP 57010B (NASA, 2000).

### 15.3.3.1 NOISE CONTROL AT THE SOURCE

Fans were the dominant noise sources within the Space Shuttle flight deck and middeck, and are now dominant in the ISS. Because of Apollo acoustic concerns, an effort was made to develop a new quiet fan under NASA research funding. Originally, this type of fan was part of the Space Shuttle design baseline, but was later dropped with some debate because of cost and schedule. Late in the design, mufflers were added to offset the fan noise. Many commercially available fans have been tested for flow, flow resistance, and acoustics, and have been cataloged to help fan selection for ISS payloads.

Quiet fans were developed for the Service Module (SM) of the ISS because the SM contained more than forty of these noise sources, and acoustic pathway improvements were not able to reduce the noise sufficiently. This state of affairs is discussed in the book “Acoustics and Noise Control in Space Crew Compartments” (Goodman and Grosveld, 2015). In order to significantly reduce noise levels in the SM, and other modules of the ISS Russian Segment, a spaceflight qualified quiet fan prototype was developed under a Remedial Action Plan (RAP) contract between NASA and the Russia-based Rocket Space Corporation-Energia (RSC-E). The funding was provided by NASA, and all technical improvements and production units were developed by RSC-E. It was decided to replace one type of fan that is used at twelve locations in the Russian SM and is also used in other Russian Segment modules (Allen and Denhan, 2011; Allen, 2015). The goals for this fan were to meet the performance characteristics of the original fan (with a flow rate of 80 l/s and 4-mm $H_2O$ pressure rise), but with a resulting uninstalled sound level of 50 dBA or less, measured at a distance of 1 m.

In order to accomplish these goals, both a quieter motor and a quieter aerodynamic design were developed for the new fan. The original SM fans were based on designs of the Mir space station fans, and included a fairly high rotational speed, with cambered flat-plate blade cross-sections with no twist to the blades. In order to meet the performance and acoustic requirements, an approach was adopted to reduce the rotational speed of the fan, but increase the blade loading to maintain the flow rate of the fan. Computational fluid dynamics methods were used to design rotor and stator cascades with aerodynamically optimized blades, including variable thickness cross-sections and twist along the blades. The cascades were fabricated using a numerically controlled machining process. The resulting performance and acoustic comparisons between the original fan (61–64 dB) and the new quiet fan (48 dB) are shown in Table 15.3.2. The quiet fan met the 50-dBA sound level requirement per the

**Table 15.3.2** Comparison of original fan and replacement quiet fan performance and sound levels (measured 1-m distance, normal to the fan)

| Fan Type | | Original fan | Quiet fan |
|---|---|---|---|
| Pressure rise | [mm $H_2O$] | | 4 |
| Flow rate | [l/s] | 47.0 | 83.4 |
| Current draw | [mA] | 470 | 470 |
| Rotational speed | [rpm] | 3120 | 2010 |
| Isolated noise levels | [dBA] | 61–64 | 48 |

RAP, and had an unloaded (uninstalled) noise reduction of about 15-dBA less than the original fan when tested in an anechoic chamber. These reductions were based on ground test data.

Even with the reduced noise levels, the flow performance of the quiet fan was significantly better than the original fan, as shown in Table 15.3.2. Because of the increased performance, it was decided to use the quiet fan to replace an additional model fan that has the same housing size, but operates at a higher pressure rise. This higher pressure-rise fan is used in several important noisy locations, including above the "kayutas" (Russian sleep stations) inside the return ducts (the primary noise source in the kayutas), and are also the main noise sources in the Mini Research Modules 1 and 2 (MRM1 and MRM2) and the Russian Docking Compartment (DC1), as discussed later. Work is currently underway to replace all SM, MRM1, MRM2, and DC1 fans of both pressure rise types with the new quiet fans, which are currently (2016) being manufactured.

Fig. 15.3.2 shows the fan blade configuration for the original SM fans and the fan blades for a prototype quiet fan. The final configuration of the new quiet fan is shown in Fig. 15.3.3.

The Russian quiet fan has significantly lowered acoustic levels in the Russian Segment. More generally, this fan provides a significant improvement in fan

**FIG. 15.3.2**

Fan blade configurations for the original and the new quiet fan (prototype).

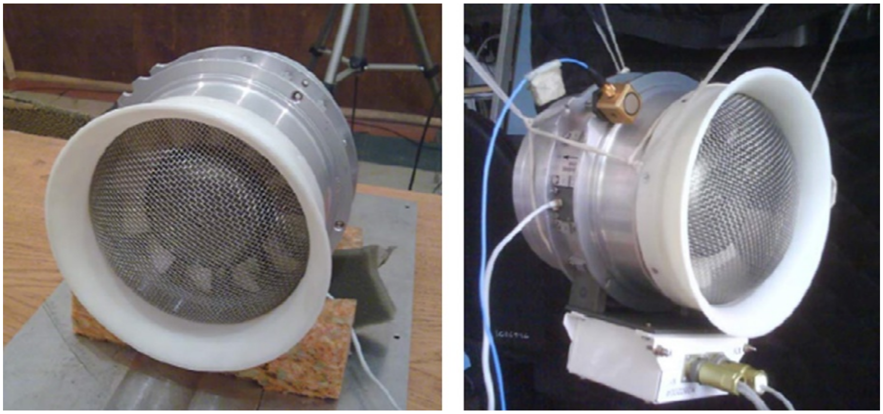


**FIG. 15.3.3**

Final configuration of the new quiet fan.

technology in manned spacecraft. As mentioned previously, the only other significant effort to quiet spacecraft fans was after the Apollo Program for the Space Shuttle Orbiter, when quiet fan technology was emphasized. Appendix D for this chapter shows the locations of fans in the SM, and the significant benefits derived from use of the quiet fans in the SM.

Fan design to meet acoustic requirements is a tradeoff involving many factors. Elements that must be matched include fan source noise, power versus frequency requirements, and size as a function of speed (O'Conner, 1995). Fan balance, blade shape, bearings, and motor design are some areas where improvements can be made to lower the noise. Reducing the fan speeds or voltage has been used where feasible to lower the noise emission levels.

Although fans are drawing most of the attention, pumps, compressors, and other notable noise sources need to be attended to in the same manner. There is technology and expertise that exists for this hardware, as there is for fans. In the case of the SM, considerable design and development efforts, funding, and costly on-orbit time has been spent on mitigation methods to remedy noise problems before quiet fans were implanted. Applying resources and technology early in a program to obtain quiet noise sources is obviously recommended.

#### 15.3.3.2 PATH NOISE CONTROL

Noisy fans generate loud airborne noise in air duct inlets and exhausts that is transmitted into the crew compartment. Inlet and outlet mufflers are commonplace accessories used on ISS to lower the noise produced by fans. A muffler or silencer used at the intermodule ventilation fan inlet and outlet in the US segment is shown in Fig. 15.3.4. It is lined inside with FELTMETAL (a micron size fiber sinter bonded into continuous felt) screen covering applied over absorbent foam material.

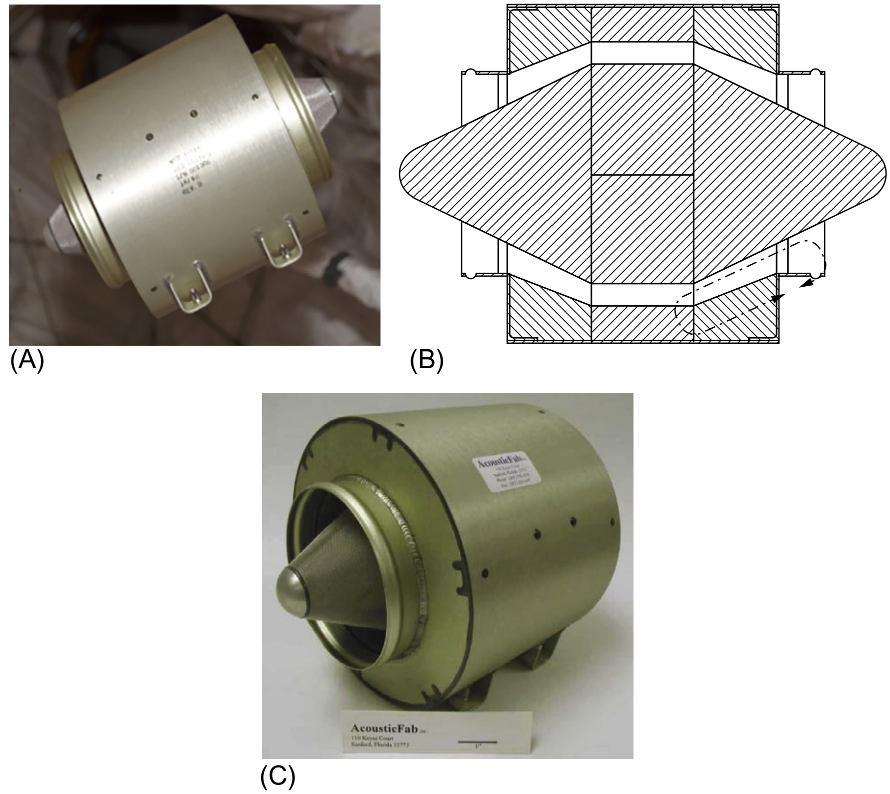


**FIG. 15.3.4**

US Laboratory IMV fan muffler and cross-section.

*Upper right-hand illustration and lower photograph are courtesy of S.A. Denham-Boeing.*

The European ISS modules use similar FELTMETAL mufflers but are lined with Kevlar, as shown in Fig. 15.3.5, for a typical muffler design and Node 2 mufflers (Marucchi-Chierro et al., 2003, 2005, 2008).

Considerable noise concerns existed for the Space Shuttle before its first flight, and government furnished equipment (GFE) mufflers were developed to quiet the effects of the most dominant noise sources, the inertial measurement unit fans (Fig. 15.3.6).

The acoustic benefits for the use of the government furnished equipment foam lined reactive and dissipative muffler designs is shown in Fig. 15.3.7 (Hill, 1992). These government furnished equipment mufflers subsequently were changed from the four individual mufflers (three inlets and one outlet), to one unified muffler.

For the ISS Functional Cargo Block (FGB), NASA developed a unique muffler (Fig. 15.3.8) incorporating improved flow, noise barrier, absorption, and Helmholtz resonator concepts that reduced both broadband and narrow band noise (Grosveld and Goodman, 2003). However, a Russian-provided muffler option was used in the

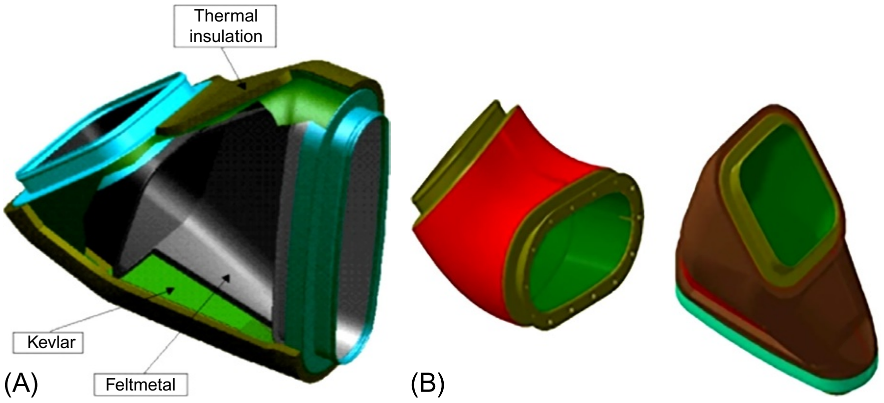


**FIG. 15.3.5**

Typical European muffler design (left view) and ISS Node 2 inlet and outlet mufflers.

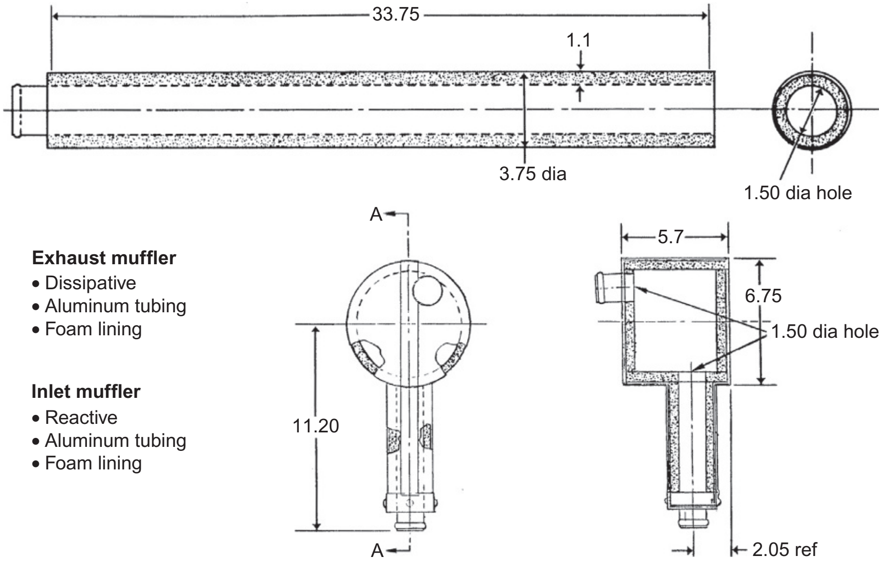


**FIG. 15.3.6**

Space Shuttle Orbiter Inertial Measurement Unit (IMU) cooling fan mufflers.

FGB, having numerous Helmholtz resonators within a rectangular shaped box-type structure, as shown in Fig. 15.3.9. This design was later replaced with an improved muffler that incorporated even more Helmholtz resonators in a rectangular box frame (Fig. 15.3.10).

Reserving an envelope and provisioning for future mufflers (scaring) should be considered in the design of space systems so that, if needed, mufflers can be added

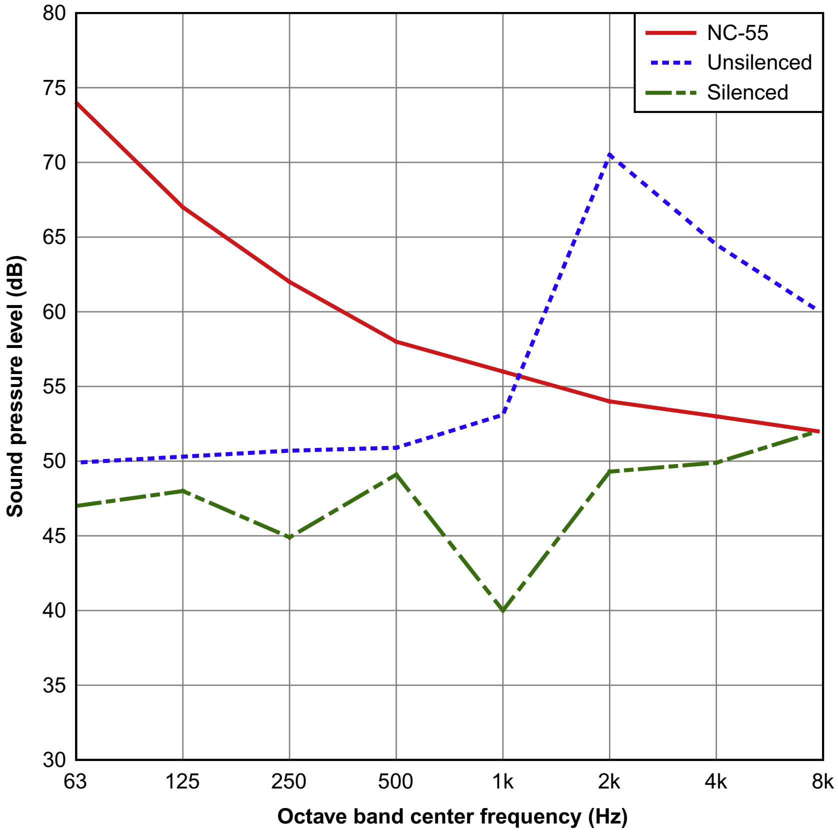


**FIG. 15.3.7**

Space Shuttle Orbiter Inertial Measurement Unit (IMU) muffler attenuation.

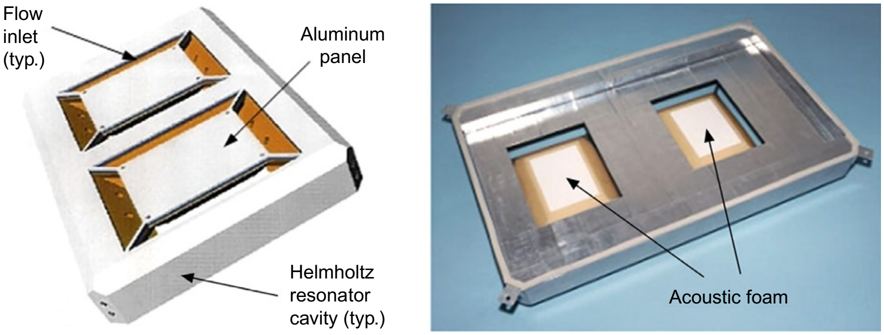


**FIG. 15.3.8**

NASA muffler for the Functional Cargo Block (FGB).

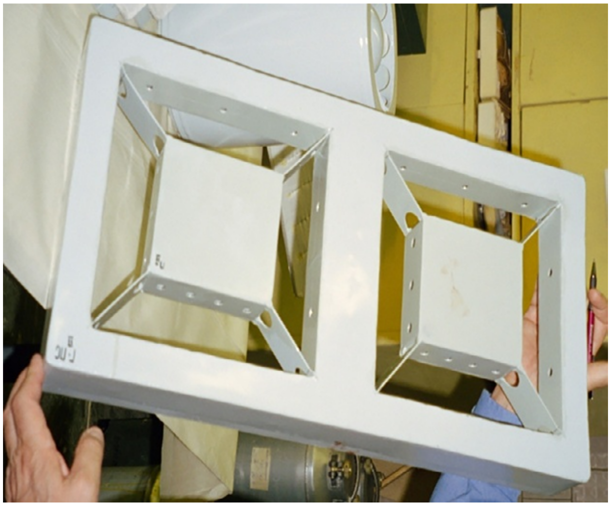
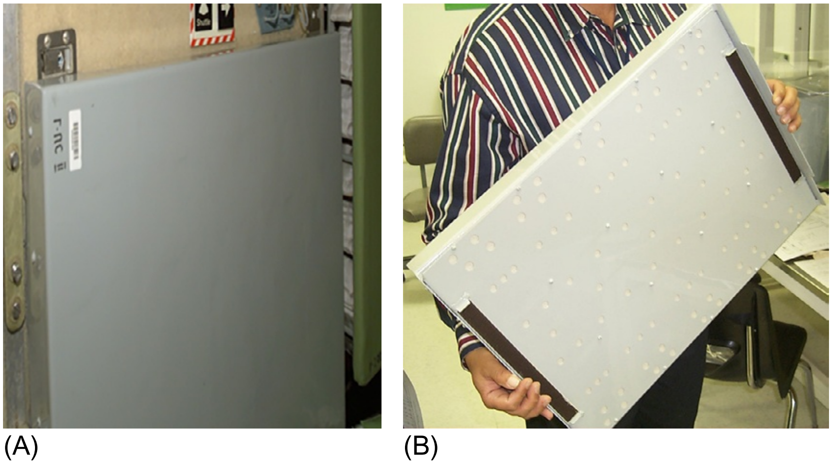


**FIG. 15.3.9**

Original Russian-provided FGB muffler.



(A) (B)

**FIG. 15.3.10**

Inboard face of muffler (left view) installed in the FGB; Outboard face of the muffler (right view) showing holes for the Helmholtz muffler approach.

later without major impacts. Air duct noise can be attenuated by improving the design of the ducts, bends, absorbent liners, and the design of diffusers or grills that draw air in or let it out. The airflow passageways to and from fans can produce noise because of restrictions and turbulent flows. They, therefore, can raise the total fan-related noise. Space Shuttle airborne noise ducting losses are shown in Fig. 15.3.11 (Hill, 1992).

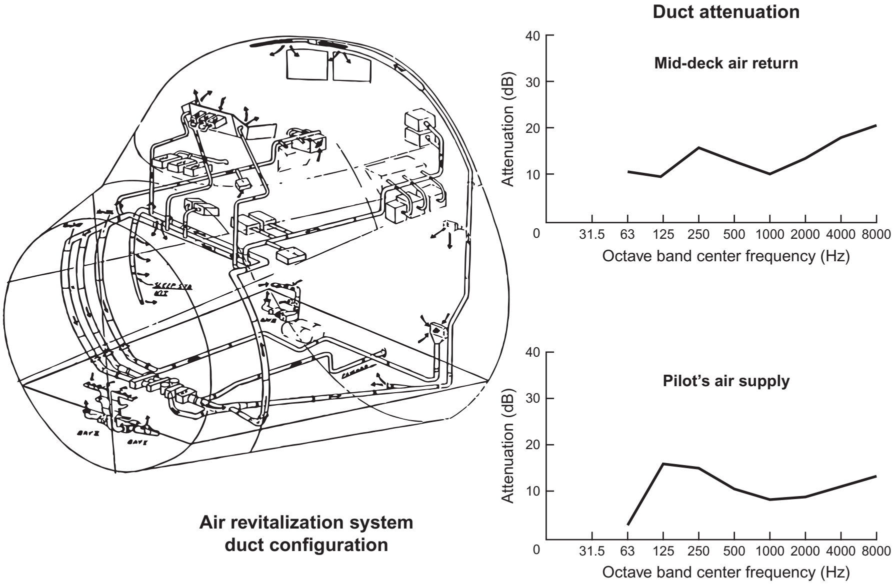


**FIG. 15.3.11**

Space Shuttle Orbiter airborne noise paths air duct attenuation.

Acoustically treated devices, termed splitters, with Helmholtz resonators tuned to attenuate fan inlet or outlet noise were added in a number of places in the ISS US Laboratory ducting to attenuate duct noise (Denham and Kidd, 1996). Similarly, ISS air inlet and outlet registers have been designed or later modified to lower the noise in the design of the outlets.

If a noise source, such as a fan, cannot be quieted by design, then strong consideration should be given to the use of a unified package that attenuates airborne emissions by using mufflers, attenuating case radiated noise by barrier applications, and reducing structure borne noise by the implementation of isolation or antivibration mounts. A good example of a system for which most of these features have been implemented is shown in an Avionics Air Assembly (AAA) fan package used in the US Laboratory (Fig. 15.3.12).

Another US Laboratory fan, the intermodule ventilation fan, illustrates several control measures, i.e., isolators and acoustic barriers, which can be implemented on fans and other noise sources as shown in Fig. 15.3.13.

Use of vibration isolation is strongly recommended to control structure borne noise by mechanically isolating fans, motors, pumps, compressors, other major noise sources, as well as the attachments of ducting and lines to them. Vibration paths in ducting-to-ducting or fan-to-ducting connections can be reduced by using rubber-type booties for connections (see right-hand view in Fig. 15.3.13). Vibration isolators are used widely in the Space Shuttle and in the ISS.

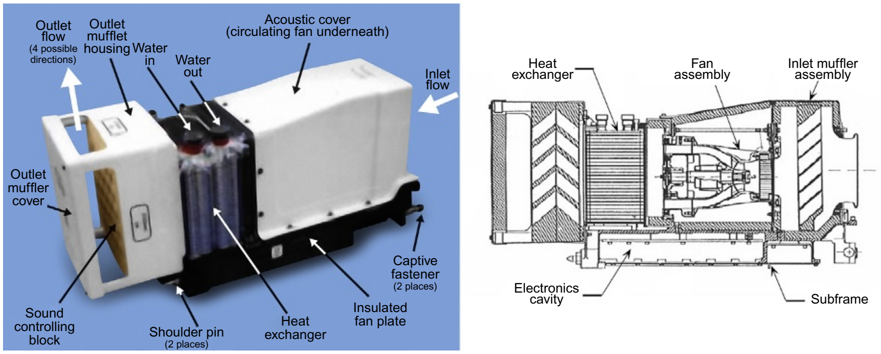


**FIG. 15.3.12**

International Space Station Avionics Air Assembly (AAA) fan and packaging.

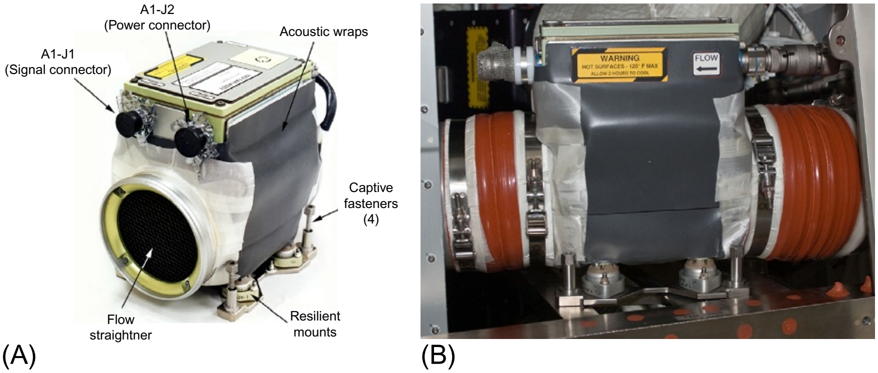


**FIG. 15.3.13**

International Space Station Inter Module Ventilation (IMV) fan.

Vibration isolators were not used to mount the Pump Package Assembly (PPA) in the ISS US Laboratory. One PPA is used in each of the two separate thermal cooling loops, each located in separate racks. The operating PPA produces high-level noises, and excites the structure of the rack within which it is mounted because of its hard mounting (Fig. 15.3.14), and its high mass and energy emission. The dual PPA units operating within the US Laboratory produced the highest continuous noise level of any source. Sound pressure levels on-orbit were measured to be very high in locations near the rack. Later, it was found that single PPA operations were feasible if the one pump loop worked at a higher rate. Even so, the resultant single PPA operation still produces the highest broadband noise and narrow band tone of all other prime movers in the US Laboratory. A PPA quieting kit has been developed to silence this hardware by improving its structural isolation and encasing it in barrier material.

NASA successfully quieted a very loud depressurization pump in the US Airlock primarily by the addition of four inexpensive off-the-shelf commercial

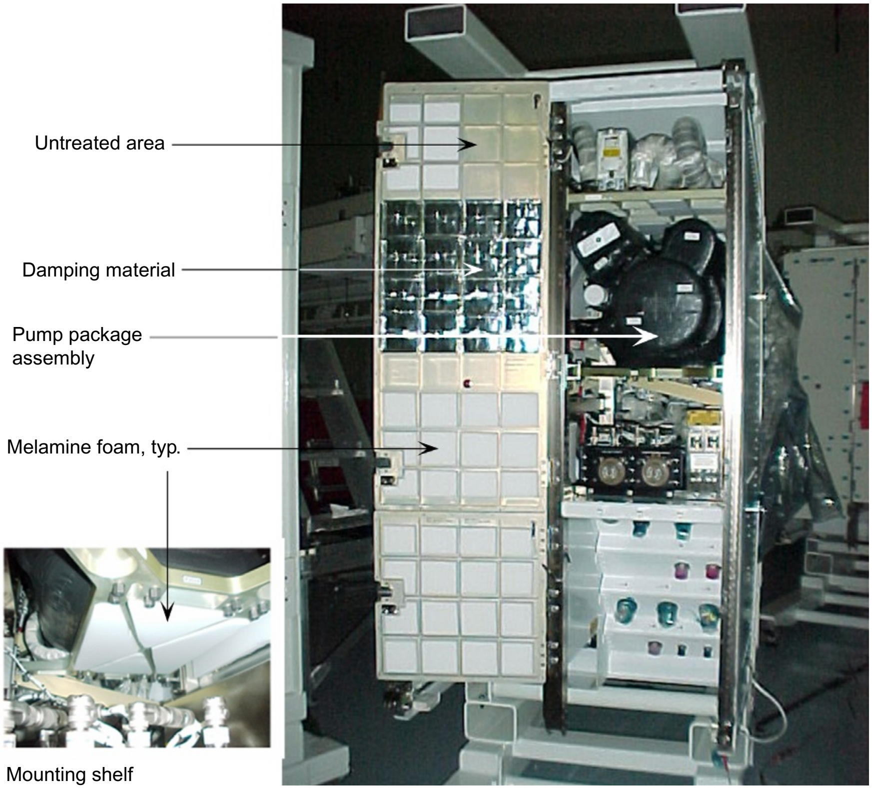


**FIG. 15.3.14**

International Space Station Rack with Pump Package Assembly (PPA).

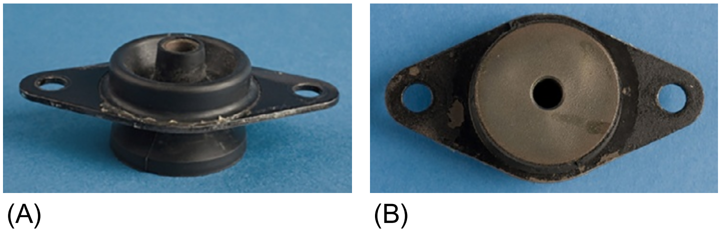


**FIG. 15.3.15**

Isolators used to quiet Russian Depressurization Pump in International Space Station.

isolators (Grosveld et al., 2003). The isolator used is shown in Fig. 15.3.15. This pump, the PPA, and the fans are good examples of where vibration isolation should be applied.

In structural borne noise situations, it is important to reduce the radiating surface area of the vibrating parts to minimize the noise emissions. Rubber pads

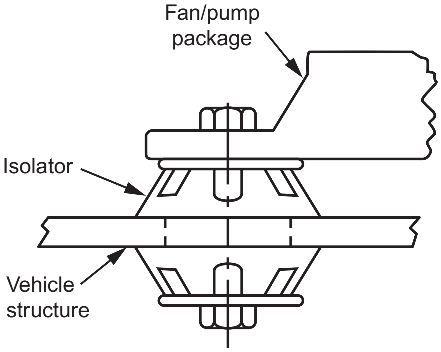


**FIG. 15.3.16**

Typical Space Shuttle isolator assembly.

have been used successfully for isolation in other ISS applications where there is insufficient room for an isolator, or to isolate ducts or tubing at their mounting to a structure. A typical isolator used in the Space Shuttle Orbiter is shown in Fig. 15.3.16.

To reduce enclosure radiation, acoustic foam has been effectively used inside a large number of ISS module and payload racks to absorb, and thus lower noise levels inside the racks. Fig. 15.3.14 shows foam added to the PPA rack interior door and to the underside of the PPA mounting shelf, as well as damping material applied to the inside face of the rack door to reduce vibrations. Fig. 15.3.17 shows three different applications in payloads where (white-colored) acoustic foam was added inside the structural enclosure to reduce the overall acoustic levels.

Barrier materials have been used on enclosures or as wraps around ducting to reduce radiated noise. These applications have been used in the quieting of the ducting in the Minus Eighty Degree Laboratory Freezer (MELFI) payload rack (Fig. 15.3.18) (Tang et al., 2003).

Various types of materials and material lay-ups have been employed to reduce emissions through rack front faces, structural closeouts, or simply as closeouts. Examples of two different effective multilayer acoustic barriers used in early ISS Temporary Sleep Station (TeSS) applications, and as Columbus cabin fan assembly (CFA) wrap are shown in Fig. 15.3.19. Materials are very important in acoustic applications and it is essential to have space-qualified materials with good acoustic properties available. Additional examples of mitigating pathway measures are provided in Goodman and Grosveld, 2015.

### 15.3.3.3 NOISE CONTROL IN THE RECEIVING SPACE

Applications of end cone foam cushions were considered for use in the US Laboratory as a way to help lower acoustic levels by changing the absorption properties of the module and the related room coefficient (Beranek, 1988). Results are shown in Fig. 15.3.20 (Goodman and Grosveld, 2015). This approach,

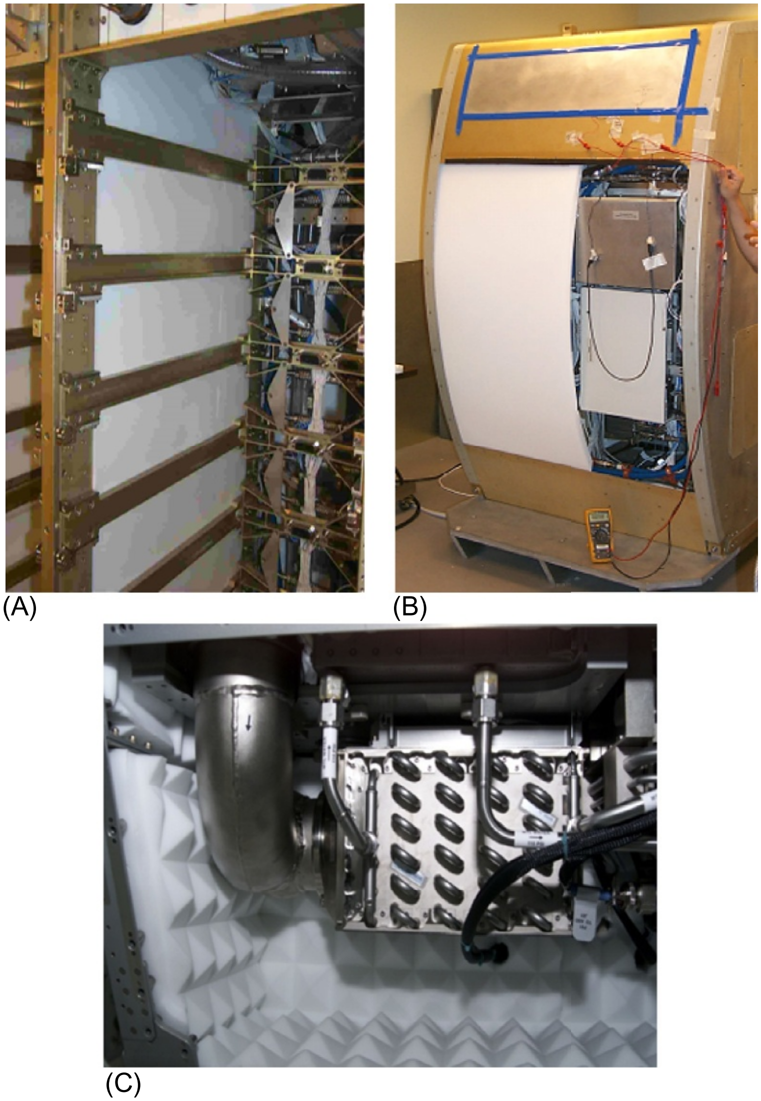


**FIG. 15.3.17**

White-colored acoustic foam used in three different ISS payloads.

although beneficial, was not used because of concerns with the cushions being damaged and contents coming out during on-orbit operations. Several Japanese ISS payloads later successfully implemented absorbent materials on the front face of their racks (Goodman and Grosveld, 2015). This area is worthy of further consideration to improve the surface absorption, if the surfaces can be made durable and reliable.

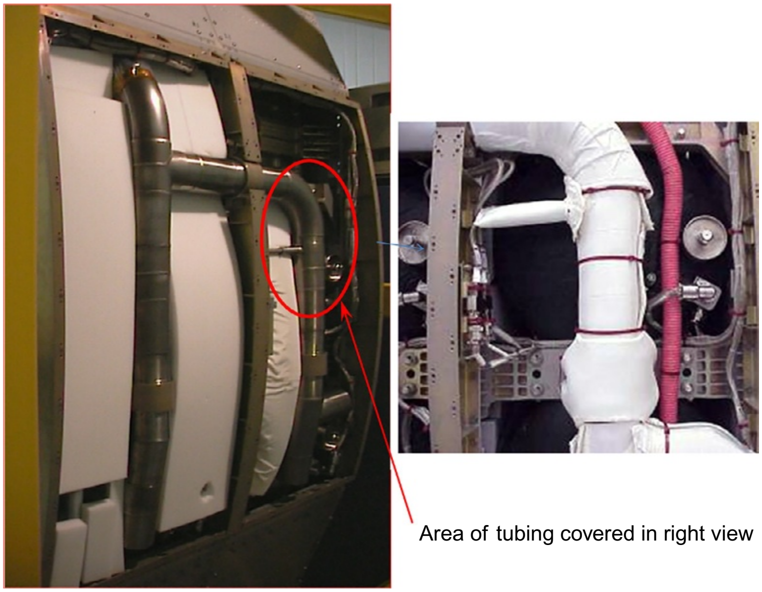


**FIG. 15.3.18**

Unwrapped ducting in the left view, and duct wrap *(white colored)* applied to the Eighty-Degree Laboratory Freezer (MELFI) payload on the right.

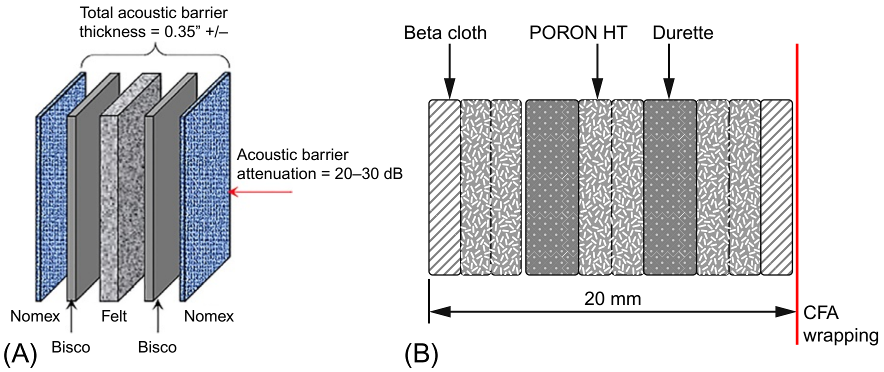


**FIG. 15.3.19**

Multilayer acoustic barriers used in early ISS Temporary Sleep Station (TeSS) applications (left view), and as Columbus cabin fan assembly (CFA) wrap on the right.

Another way to provide acceptable sound pressure levels at the receiver location is to provide special isolating enclosures like sleep stations for use by the crew during periods of rest and sleep. This approach was used in the Space Shuttle and the ISS. Such enclosures, generally designed into the crew compartment or added later as a kit, accommodate the need for lower noise levels for rest and sleep.

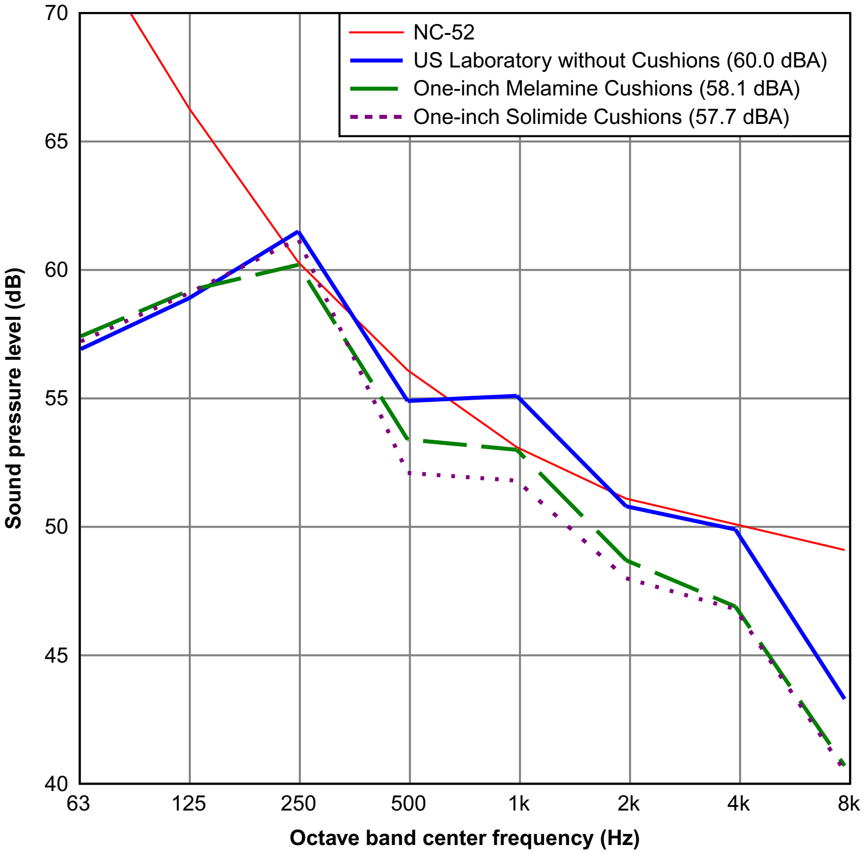


**FIG. 15.3.20**

US Laboratory Melamine and Solimide-absorbing cushions applications.

*Courtesy of S.A. Denham-Boeing.*

The provision of special, closed-off areas for exercise is an approach to lower the noise exposure to crewmembers who are not exercising. In other cases, systems can be turned off or flows can be diminished if such adjustments are acceptable. An example of this was within the Apollo Lunar Module, where fans were turned off to solve the noise interference with crew communications (Goodman and Grosveld, 2015). The use of hearing protection devices for launch, entry, and during limited applications also is an acceptable way to control levels at the receiver locations, but only for relatively short durations. Hearing protection devices have been used in Apollo, Space Shuttle, ISS, and other space programs. As can be seen from these examples, options for reducing noise at the receiver are limited, which is why efforts need to be focused and expended on effective source and path measures.

### 15.3.3.4 POSTDESIGN NOISE MITIGATION

Noise control is most effective when it is implemented as part of a normal design effort, and it should be approached in that manner. There are many examples of successful noise control efforts designed into ISS modules and payloads. Most ISS modules were successful in meeting their acoustic requirements, or being within an acceptable deviation from them. ISS payloads implemented a comprehensive noise control plan, and for the most part, were successful in obtaining compliance. A good example of this is the Human Research Facility (HRF) payload quieting efforts described in Phillips and Tang (2003).

When mitigation efforts are required to remedy an unacceptable noise situation after design completion, there is risk of considerable impacts being made to development, costs, and schedules. It can also be that late mitigation is only partially effective because the design or other impacts preclude a more effective remedy. A successful mitigation effort to limit noise along numerous pathways was implemented late in the flight assembly process for the MELFI payload (Tang et al., 2003). This effort, however, was only possible because the design allowed such modifications. It also took considerable technical consultation, design efforts, travel, materials support, testing efforts, and impacts to successfully complete.

As discussed previously, the ISS Service Module mitigation effort has taken considerable time, and has been costly in terms of funding and mission timeline impacts. Remedial pathway actions have been extensive, but insufficient to bring the module to specification levels without further work at the noise sources. The ISS FGB is another example where mitigation efforts added a lot of additional hardware after the first flights, but with basically successful results. These and other experiences show that acoustics should be considered and designed into the crew compartments and habitats early in their development phases.

### 15.3.3.5 OPERATIONAL REQUIREMENTS AND NOISE EXPOSURE

Operational requirements and “flight rules” are also used to indicate when hearing protection is needed to protect the crewmembers from noise-induced hearing loss. For example, with the 24-h, 7-day per week nature of spaceflight on ISS, a hearing conservation standard has been applied to a 16-h crew work period, and an 8-h sleep period, using a 3-dB equal energy exchange rate (NASA, 2007). According to the World Health Organization (WHO), “hearing loss is not expected to occur at LAeq,8 h levels of 75 dBA or lower, even for prolonged occupational noise exposures” (Berglund et al., 1999). [Note: LAeq is the equivalent continuous noise level (Leq) measured using the A-weighting]. This level corresponds to an LAeq,16 h of 72 dBA or lower using the internationally accepted 3-dB equal energy exchange rate. In addition the WHO states, “It is expected that environmental and leisure-time noise with an LAeq,24 h of 70 dBA or lower will not cause hearing impairment in the large majority of people, even after a lifetime exposure” (Berglund et al., 1999). This LAeq,24 h level of 70 dBA corresponds to an LAeq,16 h “work” level of 72 dBA and an LAeq,8 h “sleep” level of 62 dBA using the 3-dB exchange rate. Combined, these are the 24-h noise exposure limits applied to ISS crewmembers. The 85-dBA hazard level is applied here as a ceiling limit, where hearing protection use is required for any duration of exposure to sound levels of 85 dBA and higher, except for alarms which are subsequently silenced.

In order to assess the noise level and to take the necessary protective measures, a Noise Hazard Inventory (NHI) has been developed and provided to the ISS Mission to state when hearing protection is needed, according to the flight rule. This NHI is based on noise exposure levels measured on the ISS or calculated from ground and on-orbit sound level meter measurements and corresponding exposure durations (Limardo et al., 2015, Limardo and Allen, 2011). On-Orbit Hearing Assessments (OOHAs) also are performed periodically, to detect the onset of any hearing loss so that countermeasures can be implemented in a timely fashion.

## 15.3.4 CONCLUSIONS AND RECOMMENDATIONS

A noise control plan is essential to define and layout all of the basic efforts required to achieve resultant acoustic compliance. Included in the plan should be the overall noise control strategy and acoustic analysis approach, testing and verification plans, and focused efforts to use or develop reasonably quiet noise sources and otherwise deal with pathway treatments. The noise control plan needs to be actively monitored and efforts made to implement controls and testing as early as possible, to preclude late design and schedule impacts with flight hardware. To implement effective noise control in the design, it is necessary to understand the principles of acoustics, have noise control experience, and be able to apply these attributes to making the acoustics in the compartment acceptable. Such background and capabilities are needed by those responsible for a safe, functional, and comfortable acoustic environment in the crew compartment. It is imperative that the program management be supportive of the need to comply with established requirements, and use the noise control efforts required to achieve compliance. Support of this nature is necessary for acoustics to be successfully designed into the crew compartments and habitats.

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# 15.4 HABITAT DESIGN—SPECIAL TOPIC: RADIATION SHIELDING

**Riccardo Musenich, Martina Giraudo, Valerio Calvelli, Roberto Battiston**

## 15.4.1 INTRODUCTION

Protection of astronauts against ionizing radiation is a well-known problem to be solved in the future, long-term, manned missions in deep space. Solar particle events (SPE) and Galactic Cosmic Rays (GCR) will pose a threat the health of astronauts exposing them to poorly understood risks of several late and acute diseases, such as carcinogenesis and degenerative disease and eventually death.

Shielding from the SPE should to be not a showstopper and can be smartly achieved using the habitat mass distribution to create a shelter inside the spacecraft with a minimum addition of dedicated shielding material. Unfortunately, this is not the case when trying to shield the more energetic particles composing the GCR, which requires meters of materials to be stopped. Moreover GCR, interacting with the spacecraft structure, can create a secondary radiation environment that in some cases can be even worse than the unshielded radiation environment from a radiobiological prospective. Considering the launching cost per unit mass, it is obviously not possible to launch enough material to reduce the radiation dose as Earth atmosphere does.

Nevertheless, several research paths to partially shield the cosmic radiation have been proposed in the past years, based either on energy loss in the interaction with matter (passive shielding) or on the deflection of particles by means of magnetic or electric fields (active shielding).

## 15.4.2 PASSIVE SHIELDING

Passive shielding refers to the concept of stopping particles interposing matter between the source of those particles and the location in need of protection. There are huge limitations on the amount of mass, which can be economically launched to space; therefore, it becomes important to evaluate and choose among different shielding materials considering not only their shielding efficiencies, but also their dose reduction with respect to their mass and their eventual other purposes.

### 15.4.2.1 PHYSICS OF INTEREST

To properly understand the shielding power of a material, some nuclear physics concepts are hereafter recalled. The quasitotality of the cosmic rays spectrum of interest in space radiation protection is composed of charged particles. When crossing matter, charged particles lose their energy through a number of electromagnetic and nuclear processes, depending on their nature and energy and on the traversed medium. The underlying mechanisms are complex but it is possible to determine the rate of this energy loss through semiempirical relations.

The quantity describing the rate of energy lost by charged particles due to their interaction with matter is called the *stopping power* of the material. It is obtained considering the effects of both electromagnetic and nuclear interactions, accounted with the electronic and the nuclear stopping powers, respectively. The latter (collisions with medium nuclei) becomes important only when heavy positive charges are energetic enough to enter the target atoms, at low velocity.

The electronic stopping power changes continuously as the particles travel into the medium and it can be evaluated through the Bethe-Bloch formula, which is here reported in a compressed form:

$$-\frac{dE}{dx} \propto \frac{\rho Z z^2}{A m v^2} L(\beta) \tag{15.4.1}$$

where $L(\beta)$ is a dimensionless parameter called *stopping number*, containing the essential physics description of the process. $A$ and $Z$ are the mass number and atomic number of the crossed material and $\rho$ is its density. $z$ and $v$ are the charge number and velocity of the particle, $m$ is the rest mass of the electron (Leroy and Rancoita, 2009).

Let us focus on the dependencies underlined by the term before the stopping number: the stopping power is proportional to the square of the charge of the incident particles and to the target atomic number and density while it is inversely proportional to the target atomic mass number. It follows that, for a certain medium, the higher is the ratio between $Z$ and $A$ ($Z/A$), the better the material is able to stop charged particles, having a higher electronic density. However, when selecting a shielding material, one should consider that low $Z/A$ ratio materials, to be able to effectively stop incoming heavy ions within a reasonable thickness, should have high enough densities. As an example, hydrogen is the material with the highest $Z/A$ ratio; however at the moment, the use of hydrogen as shielding material would require huge tanks (beside complex technologies) because of its very low density. As the particle loses energy, from Eq. (15.4.1) follows that the stopping power increases and so the particle's ability to cause ionization, until it reaches a maximum, known as the Bragg peak. After this peak, the particle has lost most of its energy and is quickly stopped by the surrounding atoms. The stopping power can be view also as a measure of the effectiveness of a particle to induce ionization.

In Fig. 15.4.1 the radiation dose versus thickness of traversed High Density Polyethylene (HDPE), i.e., the energy imparted to matter per unit mass by ionizing radiation, is reported for a monoenergetic Carbon beam of 293 MeV/nucleon. One can distinctly see the Bragg peak, where most of the particles energy is transferred to HDPE.

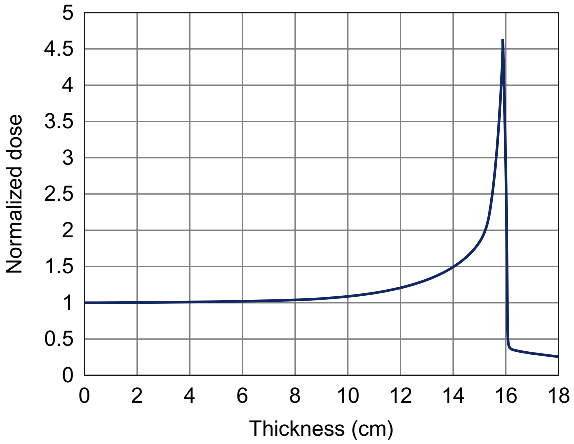

**FIG. 15.4.1**

Carbon ions 293 MeV/nucleon in HDPE simulated with the Monte Carlo code PHITS 2.80.

Incoming high-energy space ions interact with materials also through strong nuclear interactions; they can decay and fragmentize inside the traversed medium and/or strip ions, protons, and neutrons from the medium itself, leading to particle creation and nuclear breakups.

Fragmentation (break of incident ions) cross-sections have been measured by various experiments, and their dependency on the traversed medium atomic number can be described in first instance by the Bradt-Peters equation:

$$\sigma = \pi r_0^2 c_1(E)\left(A_P^{\frac{1}{3}} + A_T^{\frac{1}{3}} - c_2(E)\right)^2 \tag{15.4.2}$$

$A_P$ and $A_T$ are the projectile and target medium atomic number, respectively; $c_1$ and $c_2$ semiempirical terms, and $r_0$ the nucleon radius. It is straightforward to note that, as for electromagnetic interactions, the decrease in the atomic weight of the target medium increases the energy deposition by nuclear processes.

It can be concluded that light materials (i.e., with low atomic weight) are in principle better shielding materials than high-$Z$ alternatives.

The reader can refer to existing literature for a more detailed treatment of the underlying physics of the phenomenon (e.g., Leroy and Rancoita, 2009; Das and Ferbel, 2003). However, considering the high energies of GCRs, with nowadays reasonable shielding spacecraft thicknesses, it is not possible to totally stop them and the shower of secondary particles they unavoidably are producing. Protons and α-particles, the most abundant GCR particles, need in fact large thicknesses of materials to be stopped, making them a serious issue when designing a passive shield for space. Moreover, depending on the properties of the selected shielding material, exiting fluxes of secondary particles can equal or be even greater than the primary flux.

One risk to consider is that, as a consequence of GCR interaction with matter, the linear energy transfer (LET) of ions crossing the spacecraft shell and therefore their Radio-Biological Effectiveness (RBE) increases.

The characterization of these interactions is very challenging due to the complex nature of the GCR energy and particle spectrum: the design of the optimum shielding for a certain ion at certain energy is straightforward, on the other hand optimizing a spacecraft structure of limited mass and room to shield the all the space radiation is not. In the following paragraphs a quick summary of existing spacecraft and shielding materials is given, followed by an overview of future possibilities.

In Cucinotta et al. (2013), the authors calculated the attenuation of GCR organ averaged doses versus different depths of aluminum shielding for a year-long mission in deep space, on the Martian surface and for combined GCR and trapped protons in the ISS orbit. In deep space, after an initial decrease in the equivalent dose between 0 and 20 g/cm$^2$ of aluminum shielding, followed by a milder decrease between 20 and 40 g/cm$^2$, the values of exposure remain basically constant up to calculation limit, 100 g/cm$^2$. This is due to a quasibalance between the production of secondary radiation and loss of particles caused by the aforementioned physics processes.

When trying to protect astronauts from GCR, the energy range of interest is roughly between 100 MeV/nucleon and 10 GeV/nucleon. However, not always it is possible to have precise nuclear data and model to simulate the interaction of this radiation with spacecraft materials. For instance, significant uncertainties are found in nuclear physics models for light ions production, and their minimization is of primary importance given the impact of this component on vehicle design (Slaba et al., 2017).

For instance, Slaba et al. (2017) give a comparison that has been made between different simulation codes employing different physical models, and the resulting relative variation for total dose equivalent after a 100-g/cm$^2$ Aluminum shield was of the order of 30%.

Accelerator-based test campaigns are therefore necessary to fill the gap in these data and model. As a starting point one can use the database reported in Norbury and Miller (2012a,b), where cross-section data are organized into many categories and gaps in data relevant to space radiation protection are highlighted, as suggestion for future experiment to be made.

### 15.4.2.2 CURRENT SPACECRAFT STRUCTURES

Considering a typical International Space Station (ISS) module, the main spacecraft structures crossed by radiation are:

- The Micrometeoroid and Debris Protection System (MDPS)
- The thermal Multilayer Insulation System (MLI)
- The primary aluminum structure
- The internal outfitting materials

MDPS is traditionally composed of a first aluminum shield followed by layers of materials such as Kevlar, with very good ballistic properties, but also with a moderate radiation-shielding ability. On the other hand, MLI is very thin and can be neglected from the radiation protection point of view.

For ISS, the primary structure, which assures the pressure containment, has a typical thickness in the range 0.35–0.65 cm of aluminum alloy; the internal outfitting materials approximately give an additional contribution ranging from zone to zone from 2.1 to ~25 g/cm$^2$.

In case of a SPE, the current radiation-shielding material on board of the ISS is made by bricks of high-density polyethylene (HDPE), which, once assembled together, compose the so-called Personal Radiation Protection System (PRPS). The PRPS is a system of walls that can be erected in different locations inside the spacecraft, whenever needed, reaching thicknesses of about 5 cm with various lengths and widths. However, HDPE does not well tolerate extreme temperature cycles and cannot be used outside a spacecraft.

### 15.4.2.3 SHIELDING OF FUTURE DEEP SPACE HABITAT

In previous paragraphs it has been shown that, at least for space applications, the most important parameter for passive shielding evaluation from physics prospective

**Table 15.4.1** *Z/A* ratios reported for different materials

| | ***Z*** | ***A*** | ***Z/A*** |
|---|---|---|---|
| $^{1}$H | 1 | 1 | 1 |
| HDPE | N/A | N/A | 0.571 |
| $^{12}$C | 6 | 12 | 0.50 |
| $^{27}$Al | 13 | 27 | 0.48 |
| $^{48}$Ti | 22 | 48 | 0.46 |
| $^{207}$Pb | 82 | 207 | 0.40 |

is the ratio between its material charge and atomic mass number. In the Table 15.4.1, *Z/A* ratios are reported for different materials.

Considering the mass limitation, another way to compare different shielding solutions is to rank them by their dose reduction per unit mass, while the thickness can be considered a secondary parameter.

Generally, the following criteria should be evaluated when selecting a shielding material:

- *Z/A* ratio, linked to dose reduction per unit mass
- Density, determining the volume of the shielding
- Compatibility with the launch/external/internal environment (e.g., ability to tolerate launch vibration, vacuum environment, UV and radiation exposures)
- Safety (e.g., the material should not release poisonous elements, be flammable)
- Cost and Technology Readiness Level (TRL)

Cost should be naturally subordinated to the other parameters to allow safer deep space travels.

Considering the physics of radiation interaction with matter, it is straightforward to understand that the generic guideline when designing future exploration spacecraft is to prefer low-*Z* materials, sufficiently dense, when possible.

Hydrogen is potentially the best shielding material when considering the *Z/A* ratio; however its exploitation is very impractical even if throughout the years many visionaries proposed different concepts such as solid or liquid hydrogen tanks distributed around the spacecraft. A viable solution is to select materials with high-hydrogen content or doped with hydrogen for every structure present on board and, generally, to prefer assemblies made of structural polymers to their metal alternatives everywhere in the spacecraft. In fact, one must remember that radiation interacts with every medium on its way; therefore, every structure and material present on board of a spacecraft will contribute to the definition of the final radiation field inside a habitat and, eventually, to the crew exposure. For instance, primary structures made of carbon-based fibers ($Z_c = 6$, $A_c = 12$) instead of aluminum ($Z_{Al} = 13$, $A_{Al} = 27$) will stop radiation more efficiently for the same amount (i.d. mass) of material and will generate a lower number of secondary particles.

Aluminum, when traversed by heavy ions from the space environment, is in fact a great emitter of secondary neutrons, which can be even more biologically damaging than the incoming primary radiation. Carbon shielding could be one of the most practical solutions when all the mentioned issues are considered. It has an ability to well tolerate thermal cycles and it can also be used outside the spacecraft.

Water is also a good radiation shielding, with similar shielding properties of polymers, but has to be treated as special case, being in fact unavoidably present on board. Considering the constraints on launch mass, it would be smart to homogeneously distribute water circuits and tanks present on board over a certain area to provide additional radiation protection to the crew and save mass in the meanwhile. Liquid water necessarily needs temperature control to avoid freezing or boiling; therefore, it is the author's opinion that it should be used as shielding only inside the spacecraft (or the suit during a planetary EVA).

Lithium and Boron are low-$Z$ materials and, as such, potentially good radiation shielding. Lithium is solid at ambient temperature but unfortunately very reactive chemically. It could be however added to other materials (such as carbon) considering its low-$Z$ and its high ability to absorb neutrons. Similarly, Boron, whose isotope B-10 is used as neutron shielding in nuclear reactors, would be a very good low energy neutron absorber, for instance in planetary application where the neutron albedo is mainly not so energetic as secondary neutrons produced in a deep space habitat.

As regards solutions for planetary exploration, of course water could be extracted from the Moon or from Mars soil, it would be a practical shielding solution both for planetary or space systems.

Lunar regolith, when hit by the cosmic radiation, emits neutrons with a broad energy spectrum, and particular attention should be given to this component of radiation, usually not present in deep space habitat.

Additive manufacturing could be used on the Moon to agglomerate moon regolith into complex structures. On the Moon, gravity is about 1/6 than on Earth and the weight of concrete structures would be easier to bear. Solar energy could be employed to power additive manufacturing machines, with or without the necessity to use water. In this way, it would be possible to dispose of large amount of materials and structures without being forced to launch them from Earth.

This technology would foster not only Moon habitat protection, but also deep space spacecraft. Lunching materials from the Moon and then using them as space habitat outer shells would allow the production of thick shielding without the efforts (and the expense) to send them from Earth.

Of course, this scenario would require the development of a broad range of technologies, to be used in vacuum and zero gravity environment, such as excavating and bagging machines, additive manufacturing devices.

### 15.4.3 ACTIVE SHIELDING

Active Shielding is a class of methods to deflect charged particles through electromagnetic fields or plasma before they hit spacecraft habitat. Active shielding devices can act as sole habitat protection or can be used in support of a passive shield. During the last decades, several methods of active shielding systems have been investigated. They include the use of electrostatic fields, plasmas, confined magnetic fields, and unconfined magnetic fields.

To be attractive, active shielding systems need to achieve the following goals:

- Substantial reduction of the cosmic rays flux (both SPE and GCR).
- Minimization of secondary particles and bremsstrahlung radiation generation.
- Reduction in the mass of the spacecraft when compared to an equivalent passive shielding.
- High safety degree (the shield must not compromise astronauts' health and mission goals).

- Electrostatic

  Electrostatic shielding is based on the Coulomb attraction/repulsion force: proper armatures are charged to reject incoming particles or to attract them far from the habitat.

  Such devices manifest hard drawbacks due to the nature of the shielding itself: depending on the charges over the armature of the shield, particles with same charge are deflected, while particles with opposite charge are attracted. Due to the composition of the cosmic rays, the most efficient choice consists of charging positively the armature. As a consequence, electrons are attracted and the armature electrostatic charge decreases. To maintain the required charge, a continuous power supplying is necessary. Some studies (Townsend, 2001) have agreed that the estimated power is of the order of hundreds of megawatts to provide an electrostatic field over 200 MV/m, the minimum value to be effective. Electrical breakdown considerations limit the minimum size of the shield to dimensions of the order of hundreds of meters.

  Another concern regards the bremsstrahlung radiation produced by the electrons accelerated by the electrostatic field, which increases the radiation dose absorbed by astronauts.
- Plasma

  The plasma radiation shield is an active device, which uses electrostatic field to repel positively charged particles and magnetic fields to confine an electron cloud around the spacecraft. The electron cloud has the function to deflect the incoming electrons. Early studies of plasma radiation shielding focused on protecting against SPE (Levy and Janes, 1966). Technological challenges include means to achieve electrostatic potentials on the spacecraft surface exceeding 200 MV, control of possible instabilities in the plasma cloud and handling of huge magnetic field energy stored in the plasma.
- Magnetostatic

  Magnetostatic shielding is based on the deflection of the incoming particles via the Lorentz force. Different from the electrostatic field, which provides energy to break the particles, Lorentz force does no work on particles. Consequently, magnetostatic shields do not need, in principle, to be continuously powered. At present, magnetic shielding is considered the only possible alternative to passive shielding for spacecraft protection.

Magnetic shielding requires electromagnets surrounding the habitat. If they are wound with superconductors, no Joule dissipation occurs and power is required only during charging up. Superconducting magnet can operate without external supply for many years. As an example, magnets for magnetic resonance imaging, commonly used for medical diagnostic, lose in 1 month only few parts per million of the circulating current. Moreover, superconductors carry very high current density; therefore, superconducting magnets are much lighter than normal electromagnets.[1] However, the construction of superconducting magnets for radiation shielding would have been unthinkable 55 years ago when the principle was first proposed (Levy, 1961). At that time and for many decades, superconductors have required complex cryogenic equipment and large liquid helium reservoir, a great drawback for their use in space. Now, thanks to the development of high-temperature superconductors and the progress in cryogenics and magnet technology, magnetic shielding has finally become a conceivable option. Superconducting wires based on magnesium diboride ($MgB_2$) embedded in titanium, which can operate at temperatures above 10 K, have been proposed for space propulsion (Alessandrini et al., 2006) and radiation shielding (Spillantini, 2010; Battiston et al., 2012). The density of the Ti-$MgB_2$ composite is about 4000 kg/m$^3$ and its relatively high operation temperature ensures magnet stability.[2] A prototype of the wire was recently developed (Musenich et al., 2016).

The existing literature reports several studies about magnetic shielding of space radiation (Sussingham et al., 1999); however, until recent years all of their evaluations on shielding efficiency were based on the sole particles deflection by means of magnetic field, neglecting the interactions of particles with the materials surrounding the spacecraft and composing the magnet. Materials act as passive shielding, stopping part of the incoming charged particles, but the interactions also generate secondary particle showers, which give an additional contribution to the astronauts' radiation dose. Recent studies have shown that the particle-material interactions results in a limitation of the effective shielding power of most shield configurations (Vuolo et al., 2016).

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[1] Superconducting wires have very high critical current densities (in the order of 109 A/m$^2$ at 4.2 K and 4 T, as an example). However, the maximum current density in a superconducting magnet is not only related to the critical current density of the wire but also to quench protection. Quench is a local sudden transition to the resistive state which rapidly propagates to the whole magnet. In case of quench the stored energy is dissipated in the magnet increasing its temperature quickly and unevenly. Quench can damage the magnet if the energy density, i.e. the ratio between stored energy and mass of the winding, is too high and if the magnet is not correctly protected. Large superconducting magnets similar to those to be designed for radiation shielding have energy density up to 11 kJ/kg. It is reasonable to foreseen that such a limit can be pushed up to 20 kJ/kg, that means that a 1 GJ magnet will weight not less than 50 tons.

[2] Stability of a superconducting magnet is its capability to adsorb disturbances (energy releases) without quenching.

## 15.4.4 MAGNETOSTATIC SHIELDING CONFIGURATIONS

Many different configurations have been investigated by US and European groups. They can be listed in three different categories: large turns, solenoids, and toroids.

### 15.4.4.1 UNCONFINED MAGNETIC FIELD—LARGE TURNS

Unconfined magnetic field configurations typically mimic the dipole-like magnetic field of the Earth. A cylindrical- or toroidal-shaped spacecraft is surrounded by a dipole-like magnetic field. The magnetic field is often assumed to result from the current passing through coils on the spacecraft or on the skin of the spacecraft itself. Systems composed of large turns, sometimes with a radius order of magnitude larger compared to the habitat size, permit the generation of a weak but unbound magnetic field in the space. The shielding principle is based on the existence of a magnetic dipole exclusion region for charged particles as stated by the Störmer theory (Cocks et al., 1997). However, the approximation of dipole field generated by a single coil is valid only at great distance from the coil itself and cannot be applied within it. Accurate calculations made taking into account the multipole components of the magnetic field, show that shielding based on large turns is not effective (Shepherd and Kress, 2007).

### 15.4.4.2 SOLENOIDS

A solenoid is the simplest structure, which can be thought to generate a strong magnetic field. A large solenoid surrounding the habitat could generate a field able to shield the incoming charged particles (Fig. 15.4.3); however, such a simple system has a major drawback: the crew and the equipment are permanently exposed to a static magnetic field and, in case of fast damp (quench) also to a varying magnetic flux. To avoid unwanted, possibly harmful effects, the system requires a smaller, coaxial solenoid with opposite current to cancel the field inside the habitat as shown in Fig. 15.4.2. Of course, such a solution has a size limit related to the launcher dimension. Such a limit could be overcome by the development of technologies allowing winding the magnet in space.

Another configuration is possible using solenoids: several magnets are positioned around the habitat, again with a central solenoid used to cancel the field, as shown in Fig. 15.4.4. The second configuration was the main object of a study carried out in the framework of the NIAC-MAARSS project (Westover et al., 2011). With respect to the concentric solenoids, it has the advantage that the magnet system could be assembled in orbit, after having launched all the magnets.

### 15.4.4.3 TOROIDS

Superconducting toroidal magnets are used in both high-energy physics and nuclear fusion research. While an ideal toroidal field is generated by current (azimuthally

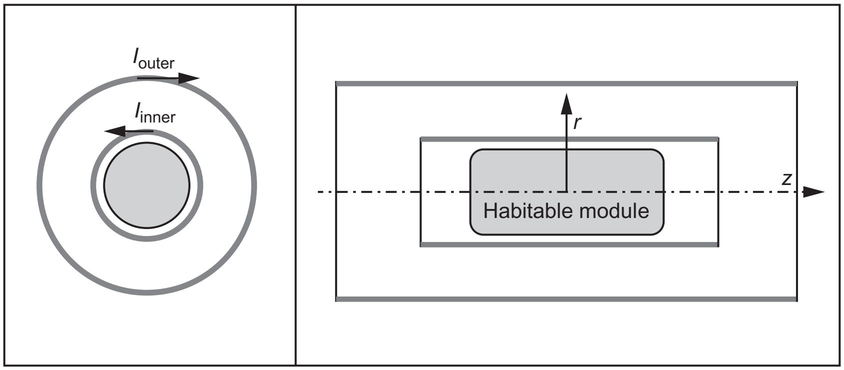

**FIG. 15.4.2**

Schematic view of the coaxial solenoid configuration.

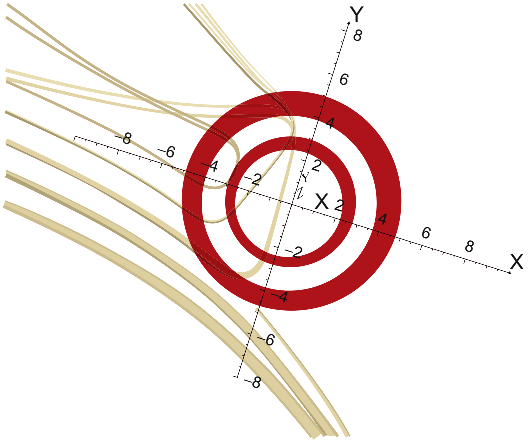

**FIG. 15.4.3**

Tracking of 350-MeV protons directed perpendicular to a coaxial solenoidal shield performed using the simulation code Opera (Cobham).

uniform) flowing on a toroidal surface, real toroidal magnets are composed of a limited number of coils, generally racetrack, circular or D-shaped. Examples of large superconducting toroids are the ATLAS barrel and end-cap magnets operating at CERN (ten Kate, 1999) and the huge magnet of the ITER project, at present under construction (http://www.iter.org).

Ideal toroidal magnets generate magnetic field with only azimuthal component and confined within the torus. Such characteristics make toroids suitable to be used in space radiation shielding (Battiston et al., 2012; Spillantini et al., 2000; Hoffman et al., 2005; Choutko et al., 2004; Musenich et al., 2014b): if a toroid is positioned to surround the spacecraft as shown in Fig. 15.4.4, sideways incoming particles are

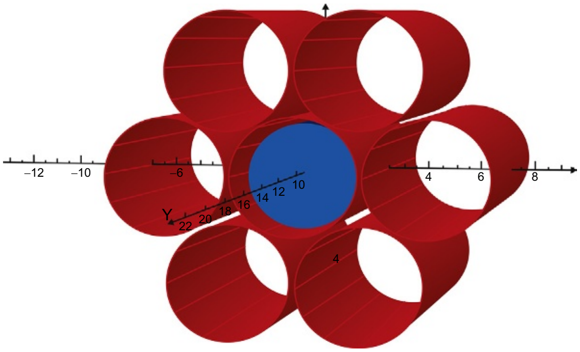

**FIG. 15.4.4**

Opera model of the multisolenoidal configuration, composed of six solenoids around the habitat *(blue)*. A central solenoid cancels the magnetic field inside the habitat.

deflected away from the habitable module. As particles coming back and forward do not cross the magnet, additional end cap shields are necessary, which can be passive or active, i.e., smaller toroids. It must be noted that real toroids, composed of $N$ coils, generate a magnetic field, which is not purely azimuthal but is rippled with period $2\pi/N$ and spreads out of magnet boundaries. However, if the number of coils is large enough ($N > 10$), the magnetic field ripple does not affect the shielding power and the stray field inside the habitat can be kept below the allowed limits, assuring a safe environment for astronauts (Battiston et al., 2013).

The shielding power of an ideal toroid can be evaluated analytically. Fig. 15.4.5 shows a schematic view of the toroidal shield where the axes and variables used later are defined. Due to the system symmetry, cylindrical coordinates are the most appropriate to describe the particle motion.

It can be demonstrated that a particle moving in the $r$–$z$ plane with zero angular speed is the most penetrating one, so the shielding power of the toroid can be written as (Battiston et al., 2013):

$$\Xi = \int_{R_i}^{R_e} B_\vartheta \, dR = \frac{\mu_0 NI}{2\pi} \ln \frac{R_e}{R_i} \qquad (15.4.3)$$

$$\Xi = \frac{m_0}{q} c\sqrt{\gamma^2 - 1}\left(1 - \sin\varphi\right), \qquad (15.4.4)$$

where $m_0$ is the rest mass, $q$ the charge, and $\gamma$ is the Lorentz factor. The analytical solution allows calculating the cutoff energy in the worst case, i.e., when $\varphi = -\pi/2$:

$$K_\eta = -\frac{E_0}{\eta}\left(1 - \sqrt{\left(\frac{q}{2m_0}\frac{\Xi}{c}\right)^2 + 1}\right), \qquad (15.4.5)$$

where $\eta$ is the number of nucleons.

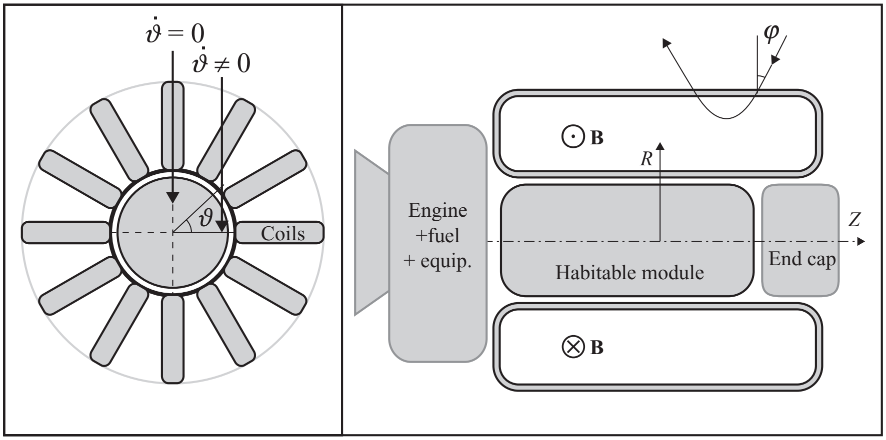

**FIG. 15.4.5**

Schematic view of a toroidal radiation shield. The trajectories of a particle with angle of incidence $\varphi$ is shown.

Assuming an isotropic flux and using the spectra of the CREME database (crème.isde.vanderbilt.edu/CREME-MC), it was calculated that an ideal, infinitely long toroid, with $\Xi = 5\ \mathrm{T \cdot m}$ is able to shield almost 80% of the incoming particles. Of course, such a reduction does not correspond to an equal diminution of the radiation dose.

As in case of other magnetic configurations, the state of superconducting technologies confined early studies on toroids for radiation shielding to only the evaluation of the magnetic field efficiency to deflect particles. Only recently, studies of the shielding power of real magnets were performed. The first of such studies (Battiston et al., 2012, 2013) was done by an INFN[3] group within the framework of the ARSSEM project funded by the ESA, where an hypothesis on the mechanical structure and an evaluation of the mass was carried out. Later (2013–15), an extended study on toroidal shield was continued in the framework of the EU-SR2S project (sr2s.eu).

In principle, toroids could be constructed in sectors and then assembled in orbit. A challenging technology is required but it allows partially overcoming the limitation due to the launcher size (Musenich et al., 2014a) (Fig. 15.4.6).

Toroidal shields have a main drawback: the huge inward radial force requires a robust and heavy mechanical structure. Even considering the availability and readiness of low-density materials like Al-$B_4C$ composites coupled with honeycomb structure, the weight of the inner support would still be a major entry in the spacecraft mass budget. A 10-m long toroidal magnet, $7.9\,\mathrm{T \cdot m}$ of bending power, wound with Al-Ti-$MgB_2$ conductor, with mechanical structure based on Aluminum alloys and composites, would weight more than 100 tons.

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[3] The Italian National Institute for Nuclear Physics.

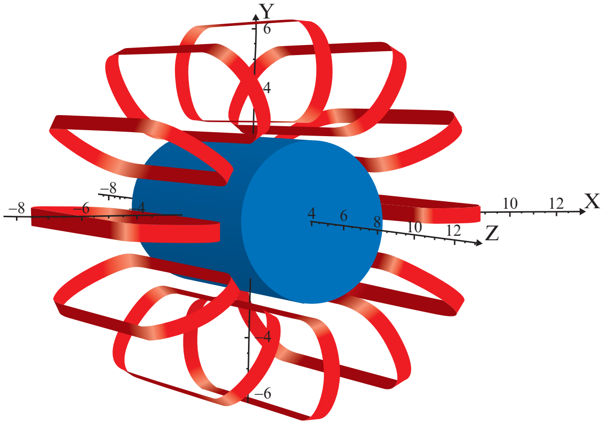

**FIG. 15.4.6**

Model of a 12-coil toroidal magnet surrounding the habitable module (in *blue*).

It could be argued that the large mass distributed around the spacecraft act as passive shield enhancing the shielding power. However, interactions of energetic cosmic rays with matter always generate secondary particles including neutrons, which are not deflected by the magnetic field; moreover, the active shielding materials would not be optimized to passively shield the incoming radiation. The result is a limitation in the shielding power. Monte Carlo simulation showed that a hypothetical immaterial toroid with shielding power 7.9 T · m reduces the dose equivalent to about 65% of the dose adsorbed by an astronaut traveling in an unprotected spacecraft. If the materials composing the magnet are introduced in the simulation, no further reduction of the dose is observed (Vuolo et al., 2016).

Such issues were faced in the framework of the SR2S project leading to a novel shield configuration still based on toroids but arranged in such a way their axes are directed radially toward the spacecraft as shown in Fig. 15.4.7 (Calvelli et al., 2017).

It must be noted that the field of an ideal toroid is fully confined; therefore, a set of quasiideal toroids leaves a lot of unshielded areas between them. In order to guarantee shielding all around the cabin the field must to be not confined; consequently, toroids must be composed of a small number of coils (according to simulations, three is the optimum). The number of toroids composing the shield is matter of optimization and depends on the maximum allowable dimension and on the spacecraft size. It is worth noting that the toroids can be launched separately and assembled in orbit. Fig. 15.4.7 shows a particular arrangement with 4 toroids, positioned at about 3.5 m from the spacecraft axis. Each toroid is composed of three coils, 120 degrees apart. Despite its spread, the magnetic field within the cabin is kept low enough to affect neither the astronauts' safety, nor instrument operation. With respect to the previously described configuration, the new one does not need a massive inner structure. Moreover, its mass is distributed in such a way to less interact with incoming charged particles.

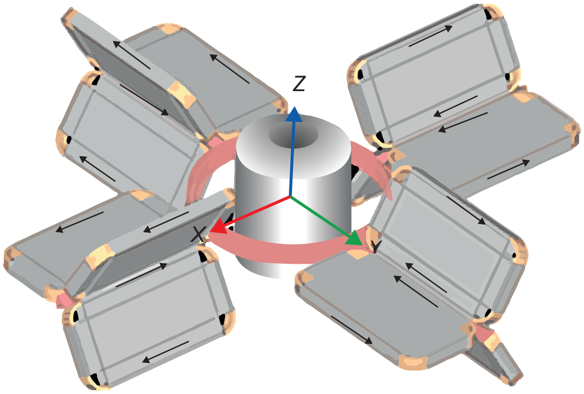

**FIG. 15.4.7**

Scheme of the novel shield configuration: toroid axes are perpendicular to the spacecraft axis. *Arrows* indicate the direction that the current should have to produce the shielding effect.

Consequently, it generates less secondary particles. Monte Carlo simulations of the equivalent radiation dose due to GCR show that the shielding power of the described configuration is equivalent to that of a toroid in coaxial configuration having a total mass of at least 80 tons. The equivalent dose due to GCR is about 55% respect to that adsorbed by an astronaut within a cabin without any protection (Calvelli et al., 2017). It must be noted that the described magnets offer a complete protection against solar radiation.

## 15.4.5 REMARKS ON SPACE RADIATION SHIELDING

The large mass required for passive shielding is an undeniable drawback partially mitigated by the necessity, in long deep space trips, to carry large amount of materials anyway (including water), which can be smartly arranged around the habitable module. On the other hand, active shielding allows using less mass to protect the crew but requires a challenging technology well above the present state of the art. Moreover, an active system is subjected to failure risks. While redundancy can be applied to the ancillary devices, superconducting magnets cannot be doubled due to their large mass; therefore, risk can be only mitigated to a certain extent. A possible way to proceed is to design magnets with groups of coils separately supplied in such a way the system can partially continue work in case of damage, with reduced power.

For future active shielding development, it is promising the idea of a protection system based on the synergetic union of passive and active shields: open magnetic structures like the previously described toroid nonaxial assembly could be coupled with hydrogen-rich materials. In this case a small volume, shielded by low-$Z$ materials walls, can be included and used as sleeping room to further reduce the dose in nominal conditions and as shelter to protect astronauts in case of failure of the active system.

As a final remark, it must be reminded that the accuracy of any evaluation of the dose is limited by the uncertainties on the knowledge of particle spectra, of all the involved nuclear processes and of all the biological effects, as well as of their impact on health. The dose adsorbed by the astronauts in a shielded habitat is due to high-energy particles, the low portion of the spectrum being filtered by the shields. Future projects on space radiation shielding must involve systematic studies aimed to deepen the scientific knowledge mainly in the high-energy region of the spectra.

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