# ACOUSTICS

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## 1.1 Acoustics safety issues

The acoustics environment in space operations is important to maintain at manageable levels so that the crewperson can remain safe, functional, effective, and reasonably comfortable. High acoustic levels can produce temporary or permanent hearing loss, or cause other physiological symptoms such as auditory pain, headaches, discomfort, strain in the vocal cords, or fatigue. Noise is defined as undesirable sound. Excessive noise may result in psychological effects such as irritability, inability to concentrate, decrease in productivity, annoyance, errors in judgment, and distraction. A noisy environment can also result in the inability to sleep, or sleep well. Elevated noise levels can affect the ability to communicate, understand what is being said, hear what is going on in the environment, degrade crew performance and operations, and create habitability concerns. Superfluous noise emissions can also create the inability to hear alarms or other important auditory cues such as an equipment malfunctioning. Recent space flight experience, evaluations of the requirements in crew habitable areas, and lessons learned (Goodman 2003; Allen and Goodman 2003; Pilkinton 2003; Grosveld et al. 2003) show the importance of maintaining an acceptable acoustics environment. This is best accomplished by having a high-quality set of limits/requirements early in the program, the “designing in” of acoustics in the development of hardware and systems, and by monitoring, testing and verifying the levels to ensure that they are acceptable.

## 1.2 Acoustic requirements

Requirements are a key pillar to successful design, and need to be as well defined and clear as possible at the beginning of a program. To be successful in meeting the requirements, acoustics needs to be treated as a technical specialization on par with other design disciplines, and experienced and knowledgeable personnel need to be assigned to implement the defined requirements. The following factors need to be considered in tailoring the requirements to meet the specific application: type of mission; mission duration; the number and characteristics of crew occupants; size, function, number, and type of hardware systems that make up the manned vehicle, module, or enclosure, and the supplementary hardware such as payloads and supplementary Government Furnished Equipment (GFE); whether single or dual shift operations will be used; the distance between crew members that is required for good communications; and the quality of the communications needed. All the requirements in this article apply throughout the crew habitable volume. Separate acoustic restrictions need to be applied to areas that are outside of this habitable volume, but which maybe accessed for short-term use, for equipment change out, or for maintenance. Special consideration should be given to the levels allowed in the habitable volume should such access require leaving open the access doors, panels, or other means. Crew compartment/habitat will be the term for the habitable volume in a manned spacecraft, module, of other types of manned enclosures used in space. Use of design “goals” in lieu of firm requirements is not recommended, as they set the stage for efforts that are essentially “do what you can do” and imply that efforts should be limited to those objectives which can readily be met, or can be so interpreted. Some important acoustic safety requirements currently employed by NASA and its international partners in manned spacecraft applications are discussed in the following sections.

### *1.2.1 Continuous noise*

Space flight missions typically range in duration from several days to many months. Special requirements are needed to safely administer the 24-hour per day, 7-day per week exposure to noise in the space vehicle environments. Noise sources operating for more than 8 hours in any 24-hour period are classified as producing continuous noise. NASA, in 1972, adopted Noise Criteria (NC) curves as an Acoustic Noise Criteria standard to manage the continuous noise in manned spacecraft (*Acoustic Noise Criteria* 1972). NC curves specify the octave band limits of the acceptable noise levels in habitable environments with all systems operating, and are commonly used in industry for defining the ratings or control of ambient noise in buildings. The acoustic environment, with the integrated GFE as part of the habitable space, is limited by the NC-50 curve shown in Figure 1. The NC curves in Figure 1 are extrapolated to include the 16 kHz octave band to better cover the audible range at the higher frequencies. [Figure 1 here]

An appropriate limit or sub-allocation must be applied for the composite of other significant hardware located within the crew compartment/habitat that is not required for the basic function of the spacecraft, module, or enclosure systems. In the past, this category included such items as payloads, non-integrated GFE, experiments, cargo, or other classifications of hardware. If these payloads and other types of hardware amount to a significant contribution, as the payload racks did in the International Space Station (ISS), then a sub-allocation for them, as a complement, should be limited to NC-48, in consonance with what integrated system and crew compartment/habitat type limits are applied (*SSP 57011-B* 2003). Each individual rack equivalent item should meet the NC-40 per Figure 1, or lower, as applicable (*SSP 57000* 2000). Appropriate sub-allocations need to be given to hardware components that make up payload rack type hardware to ensure that the rack limit is controlled. This is especially true if rack makeup or components are changed out during the operational life of the rack or hardware. An individual hardware item, which is of lower complexity than that of a payload rack, and is similar to an aisle mounted hardware item should either fit into the complement total limit or itself meet a lower limit.

The continuous acoustic levels for the integrated systems affecting the crew compartment or habitat and including the noise from supplementary hardware (payloads, non-integrated GFE, or other classifications) is then limited to the NC-50 + NC-48 (or NC-52) level shown in Figure 1. If the supplementary hardware is significantly less complex in nature than the ISS payload rack hardware and does not merit the NC-48 level allotment, the total noise in the crew compartment or habitat should be NC-50 rather than the NC-52 level. The NC-50 specification is preferred over the NC-52 level as this specification provides for improved quality of communications and word intelligibility, and was recommended for manned spacecraft in general, the Space Shuttle, and the International Space Station (ISS) (*Acoustic Noise Criteria* 1972; Pearsons 1975; Piland 1980; *CHABA* 1987). Figure 2 shows the quality of face-to-face communications expected for vocal effort and separation distance in terms of preferred speech interference level (PSIL) and dBA levels (*STD-3000* 1995). [Figure 2 here] The PSIL was established to determine the effect of continuous background noise on speech communications in a work environment and is defined as the arithmetic average of the sound pressure levels in the 500 Hz, 1000 Hz, and 2000 Hz octave bands. Figure 2 also shows the same evaluation against an A-

weighted background noise level, which uses a one-third octave band dependant A-weighting to better subjectively evaluate the response of the human ear. Figure 3 shows the percent intelligibility levels plotted versus the NC curves (or dBA levels) for crew-to-crew communication distances of 5-8 feet. Improvement in intelligibility is shown by the use of NC-50 versus the NC-52 rating (Pearsons 1975). NASA's recommended minimum percentage of intelligibility of 75% for satisfactory communication of most messages is also shown on this Figure 3. A 95% intelligibility is recommended for sentences under normal vocal effort with the talker and listener visible to each other (*CHABA* 1987). Note that the data used for this curve is based on communication between males conversing in the English language, and does not take females or foreign dialects into account.
[Figure 3 here]

The crew needs a reasonable acoustic level for their sleep periods to obtain the necessary rest and recover from any high noise exposure during their non-sleeping periods. Where the crew compartment/habitat design can allow, the sleeping area should be an accommodation separated from the work and the higher noise areas. The crew sleeping area should not exceed NC-40, as shown in Figure 1 (*Acoustic Noise Criteria* 1972; *STD-3000* 1995). To preclude awakening sleeping crewmembers, impulse or transient noises in the sleeping area should be limited to less than 10 db above the background noise (*Acoustic Noise Criteria* 1972; *STD-3000* 1995).

### *1.2.2 Intermittent noise*

Intermittent (less than 8 hours in any 24-hour period) operating hardware can be very disturbing, wake crewmen, and interfere with sleep or nominal operations. Supplementary hardware, such as that in the payload rack type of classification, should limit the intermittent A-weighted acoustic emissions to the levels and durations defined in Table 1, with the measurements taken at 0.6 m from the loudest point on the hardware (*SSP 57000* 2000). Some hardware that is part of the manned spacecraft, module, or other types of manned enclosures such as toilets, pressurized gas systems, or other stand-alone hardware of acoustic significance should be similarly controlled. Most exercise equipment like treadmills or ergometers may be difficult to control to these limits and could produce loud acoustic levels over time, depending upon crew size, etc. It is suggested that the exercise area be allotted separate quarters from other habitable areas in the crew compartment/habitat, if possible.

Table 1. Intermittent A-weighted sound pressure levels and corresponding operational limits for supplementary hardware (such as rack-type payload hardware and non-integrated GFE).

| Maximum Noise Duration per 24 Hour Period | A-weighted Overall Sound Pressure Level [dBA] |
|---|---|
| 8 Hours<br>7 Hours<br>6 Hours | 49<br>50<br>51 |
| 5 Hours<br>4.5 Hours<br>4 Hours | 52<br>53<br>54 |
| 3.5 Hours<br>3 Hours<br>2.5 Hours | 55<br>57<br>58 |
| 2 Hours<br>1.5 Hours<br>1 Hours | 60<br>62<br>65 |
| 30 Minutes<br>15 Minutes<br>5 Minutes | 69<br>72<br>76 |
| 2 Minutes<br>1 Minute<br>Not Allowed | 78<br>79<br>80 |

### *1.2.3 Narrow band components*

A narrow band component is a simple or complex tone or a line spectrum having intense and steady-state frequency components in a very narrow band (1 percent of an octave band or 5 Hz, whichever is less) and is heard as a musical sound, either harmonic or discordant. The maximum sound pressure level of any narrow band component should be at least 10 dB less than the sound pressure level of the octave band that contains the component (*Acoustic Noise Criteria* 1972; *STD-3000* 1995).

### *1.2.4 Ultrasound and infrasound*

Ultrasound is high frequency sound that is inaudible to the human ear (frequencies above 15 to 20 kHz). Ultrasonic sound can have physiological effects on humans and should be addressed, although it is thought that concerns should be focused on direct body contact and the audible noise associated with the sub harmonics of the hardware that produces it. Ultrasonic noise can be generated by electrical converters, battery chargers and other types of equipment. There are two concerns in dealing with this noise: (1) it is difficult and costly to predict if the hardware will produce levels in the crew compartment/habitat sufficient to be of concern or to exceed the defined limits; and (2) the hardware needed to measure ultrasonic emissions is not commonly available or used. Use of the extended NC curves to 16 kHz (Figure 1) will help understand most sub harmonics effects in the audible range, but it is recommended that some screening will be used to determine if the resultant ultrasonic levels in the crew compartment/habitat are of concern or will exceed the limits. The recommended limits are shown in Table 2 (*CFR 1910.95* 1998; *Threshold Limit Values* 2004). Infrasound constitutes acoustic emission below the audible range of human hearing. Infrasound in the crew compartment or habitat should be limited to 120 dB in the frequency range of 1 Hz to 16 Hz for a 24-hour exposure (*STD-3000* 1995).

Table 2. Threshold limit values (TLV) of ultrasonic sound in air.

| One-third Octave Band Center Frequency [kHz] | Ceiling Values [dB] | 8-Hour Time Weighted Average [dB] |
|---|---|---|
| 10 | 105 | 89 |
| 12.5 | 105 | 89 |
| 16 | 105 | 92 |
| 20 | 105 | 94 |
| 25 | 110 | -- |
| 31.5 | 115 | -- |
| 40 | 115 | -- |
| 50 | 115 | -- |
| 63 | 115 | -- |
| 80 | 115 | -- |
| 100 | 115 | -- |

### *1.2.5 Hazardous overall noise limits*

Excessively loud overall noise levels may cause harm to the hearing abilities of the crewmembers and should be limited. The continuous noise level during flight in the integrated crew compartment/habitat is limited to a maximum of 85 dBA at the crewmembers ear (*STD-3000* 1995). Noise from hardware associated with cabin depressurization, re-pressurization, or similar activities should be limited to 105 dBA, at the crewmembers ear, during these types of operations (*CxP70024* 2006). If such activities recur very often, then limits on the noise dose should be considered. During launch, entry or burn mission phases, including ascent abort, levels at the ear should not exceed 105 dBA (*CxP70024* 2006). Impulse sound, a change in sound pressure level of more that 10 dB in one second or less, should not exceed the 140 dB peak sound pressure level at the crewmembers unprotected ears (*STD-3000* 1995).

### 1.2.6 Reverberation time

Reverberation time is the time required for the energy density in the acoustic field to reduce to a level 60 dB below its steady state value. Reverberation time has a significant effect on speech intelligibility. The reverberation time should be adjusted to the room volume in the crew compartment/habitat, and criterion for conversational speech. The reverberation time is recommended to be no greater than 0.5 seconds in all octave bands (*STD-3000* 1995). The ISS Program specifies a reverberation time of 0.5 ± 0.1 second for the 1000 Hz octave band (*STD-3000/T* 2004). The Constellation Program uses reverberation times of less than 0.6 seconds within the 500 Hz, 1000 Hz, and 2000 Hz octave bands (*CxP70024* 2006). Higher values may cause blurring effects, imposing significant limits on the speech intelligibility in crew communications (*CHABA* 1987). Reverberation time levels up to 1 second may be considered in the lower frequencies (63 Hz and 125 Hz).

### 1.2.7 Alarms

Alarm signals used within the crew compartment/habitat should be readily heard and be discernible by crewmembers working or sleeping. Signals that come from loudspeakers or other sources such as from adjacent crew compartments or modules should produce sufficient signal-to-noise ratio that the signals can be heard over the background noise in the crew compartment/habitat that the signal needs to be heard in. NASA standards (*STD-3000* 1995, *STD-3000/T* 2004 ) have used a signal-to-noise ratio of 20 dB in at least one octave band between 200 Hz and 5000 Hz as a requirement, although *MIL-STD-1472F* (1999) calls out 10 dB as acceptable for the same frequency range. *ISO Standard 7731* (2003) and *CxP70024* (2006) uses 13 dB as an acceptable signal-to-noise ratio in one-third octave bands, and the use of this standard is recommended.

## 1.3 Compliance and verification

It is intended that the requirements and limits be met without the attenuation afforded by hearing protection or communication headsets or other coverings, except for launch, entry, burn or other short term, limited phases of a mission. An example of a limited phase would be that which occurs during cabin depressurization. Meeting the limits without these ear coverings ensures a safe and habitable environment, and precludes the use of hearing protection and other means noted, from being imposed upon the crew and being relied on to protect the crew, rather than the design implementation itself.

Frequently, the acoustic requirements in the beginning of a program are challenged, regarded too strict and considered to lead to unacceptable impacts. However, the previously discussed requirements and limits can be met if the appropriate resources and efforts, experience, and expertise are applied, especially early in the program at hand. Verification is another key pillar to a good design and verification needs to define how and what needs to be completed to prove that the requirements have been met. It is usual practice to have companion verification procedures written by the originator(s) of the requirements to ensure the verification includes how to test, demonstrate, inspect, or analyze the system to satisfy the requirements. The verification procedures need to be stated as precisely as possible to define the system test success criteria and the use of the necessary equipment. An acoustic noise control plan is required to define basic efforts and plans necessary to ensure compliance. The noise control plan should include the selection or the development of quiet noise sources and the procedures to determine and control their levels. The plan should also include development and verification testing plans and an acoustic analysis approach. The plan should be updated throughout the program to reflect completed and current status and efforts. Providing oversight and monitoring the progress of the noise control plan and the design and development efforts will help ensure an understanding and agreement with the efforts, and will contribute to full compliance. When requirements are not met, one aspect in a possible waiver or deviation assessment should be to address whether early and reasonable efforts were applied towards compliance. If proper monitoring of the design and development progress is performed, then early and reasonable efforts are addressed and attended to as soon as possible in the program. Requirements may have been perfectly written, but if they are not implemented and verified correctly, and with the right equipment, methods and experience, than the purpose of the requirements has not been achieved.

## 1.4 Conclusions and recommendations

Stringent acoustic requirements are considered necessary for current and future space flights to protect the safety and well-being of the individual crewmembers and the successful completion of their intended missions. The acoustic requirements for the habitable volume and other areas accessible to the crew, the integrated hardware, and the supplementary Government Furnished Equipment and other payloads need to be defined early in the program cycle, be implemented correctly and verified. The requirements are uniquely dependent upon the character, duration, frequency content and level of the noise source emission. A noise control plan is strongly recommended and should be updated throughout the design, the manufacturing stages and the flight phases of the space vehicle. The noise control plan, in combination with monitoring and oversight of the design, the development and the verification efforts, is essential to achieve full compliance with the defined acoustic requirements. A significant experience basis for the requirements has been presented here. A bibliography for recommended reading and websites with information on the relevant acoustic subjects is included at the end of this article. It is recommended that this information be read or consulted when needed, used to enhance understanding of the acoustics, or used as a reference for this subject.

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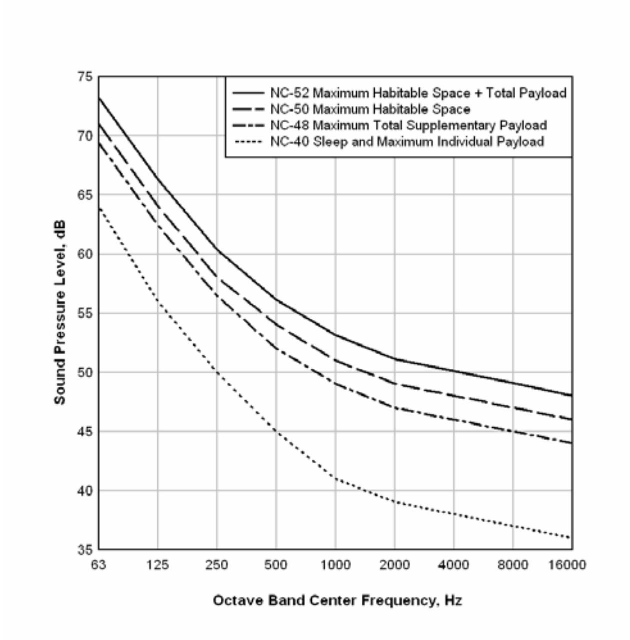


Figure 1. Extended continuous noise criteria (NC) specifications.

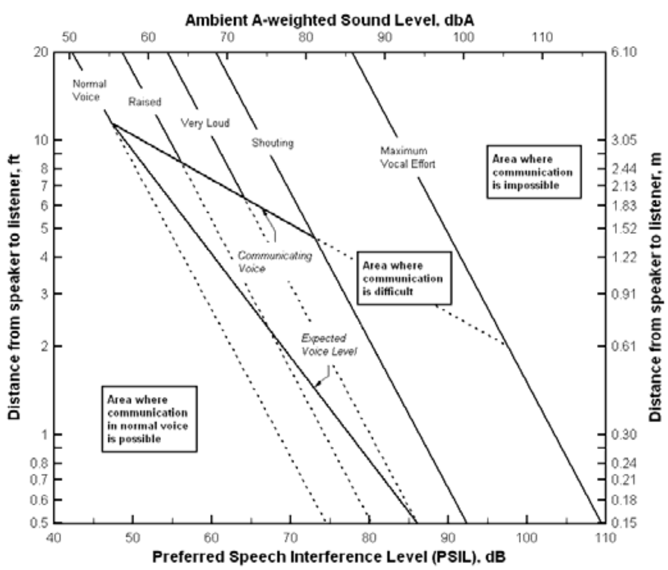


Figure 2. Effectiveness of voice communications as function of the preferred speech interference level (PSIL) or dBA noise level, and distance from speaker to listener.

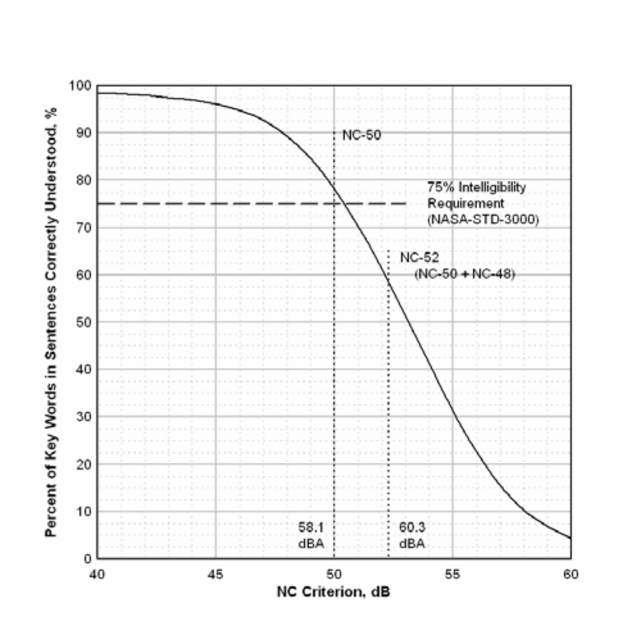


Figure 3. The percent intelligibility level plotted versus the NC criterion for crew-to-crew communication at distances from 5-8 feet.

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| 100 | 115 | -- |