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V. SOUND AND NOISE

By J. L. Homick

INTRODUCTION

Acoustical noise is largely a byproduct of technologically advanced and industrialized societies. Noise produced by the supersonic transport (SST) aircraft is but one glaring example of modern man's ability to create noisy machines.

Partly because few can avoid hearing loud sounds and partly because people are becoming more concerned with what these sounds are or may be doing to them, there has been in recent years an increased awareness of noise in public, private, and government sectors. Legislation has been created to attempt to regulate community and industrial noise. In general, the average individual in modern society is better informed regarding noise and its possible effects. This increased awareness has extended to the design and development of large manned spacecraft systems.

No attempt is made here to summarize all available noise data from the manned space program. It is sufficient to note that the designers of earlier spacecraft (Mercury, Gemini, Apollo, and Skylab) were aware of the detrimental effects of excessive noise exposure and were successful in keeping launch and on-orbit noise to safe, if not tolerable, levels. That is not to say that noise was never a problem. Reports from flight crewmen indicated that noise sometimes interfered with speech communications and disrupted sleep. For these and other reasons, acoustical noise control has received considerable attention in the design of the Space Shuttle spacecraft. How successful these noise control efforts on the Space Shuttle vehicle will be remains to be seen. Inevitably in the design and construction of spacecraft, where cost, weight, and size are critical factors, a compromise must often be reached between what is desirable and what is practical. Nevertheless, in future, more sophisticated vehicles, intended for long-duration habitation by large numbers of men and women, acoustical noise must be given due consideration as a potential detriment to safety, functional efficiency, and physical and mental health.

The purpose of this chapter is to acquaint scientists and engineers associated with the design and/or use of future spacecraft with problems related to sound and noise. The majority of the information presented is on the effects of audible sound and noise on man. Some effects of nonaudible sound (infrasound and ultrasound) are also presented. No attempt has been made to summarize all of the vast literature in this area. Instead, emphasis has been placed on those factors which have potential relevance to the space-flight situation.

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Definition and Description

In defining sound, it is appropriate to first consider the basic properties of the sound source, the transmission medium, and the receiver. Any mass which contains the physical properties of inertia and elasticity, and which has been set into vibration by the application of some energy, may be a sound source. Sound is propagated through the surrounding medium (gas, liquid, or solid) in all directions from a vibrating source. The propagation results from the fact that molecules in the medium transmit their motion to one another in a progressive, wavelike manner. That is, condensation and rarefaction phases of molecules in the medium are propagated as compression waves. Sound wave propagation is dependent on the physical characteristics of the transmission medium: inertia, elasticity or compressibility, friction, and density (ref. V-1). For the purposes of this report, the receiver of sound energy is the human body and, specifically, the auditory system, which is exquisitely constructed to transduce mechanical energy (sound) into electrochemical neural energy. The reader is directed elsewhere for a more thorough description of sound generation and propagation, as well as a description of the anatomy and function of the human auditory system (refs. V-2 and V-3).

Perceived or audible sound is of considerable value to man. It can warn him of danger and arouse and activate him. It provides him the immeasurable advantage of communication by speech and language. Sounds can elicit a variety of emotions, both desirable and undesirable.

Unfortunately, excess sound generated by sources irrelevant to the individual may arouse him with excessive frequency, may have no adaptive value, or may simply be offensive. Also, everyday experience indicates that excess sound can interfere with the perception of important, relevant auditory signals. Perhaps most important is the well-documented fact that exposure to excessive sound can cause temporary or permanent loss of hearing function.

Thus, irrelevant or excessive sound is undesirable. By definition, such unwanted sound is noise. The definition of noise often involves a value judgment; sounds that may be considered as noise by some individuals may not be noise to others. Sounds that are valuable in one location may travel to areas where they may interfere with and disrupt useful and desirable activities. Other sounds may be noises only at certain times, in certain places, to certain people. These complexities regarding the definition of noise must be kept in mind, particularly when considering certain psychophysiological and social effects of noise.

Parameters of Sound and Noise

As previously stated, the primary purpose of this report is to summarize relevant information about the effects of audible sound and noise on man. To render a discussion of these areas more meaningful, a brief description of the physical parameters of sound and noise is provided.

The basic parameters used to describe acoustical energy fields include frequency, intensity, and duration. Each of these is discussed separately in the following subsections.

Frequency.- The concept of oscillation at a particular frequency can be represented by the back and forth movement of a clock pendulum. The number of oscillations per unit time defines the frequency, which is specified by the unit hertz (oscillations per second). Audiofrequency refers to the frequencies within the normal range of human hearing, usually specified as 20 to 20 000 hertz. Ultrasound refers to frequencies above 20 000 hertz, and infrasound contains frequencies below 20 hertz.

The period of a sound is the time interval required for one complete oscillation and is the reciprocal of frequency. A sound is periodic if the value of the period (and hence the frequency) remains constant throughout its duration. Pure tones are periodic sounds. Most environmental sounds are nonperiodic, as they contain many frequency components. Such nonperiodic sounds are generally referred to as noise. (This definition of noise is not to be confused with the previous definition of noise as unwanted sound.) Wide-band noise contains a wide or large portion of the frequency spectrum; narrow-band noise contains only a narrow or limited portion of the frequency spectrum.

Since many sound effects of interest to the acoustical environmental engineer and the physiologist are frequency dependent, it is necessary to specify the frequencies which are present in a sound field. These data are usually presented in the form of a frequency spectrum, which is a plot of relative intensity as a function of frequency. Frequencies may be specified in successive octave, half-octave, or third-octave frequency bandwidths or in single cycles. An octave refers to an interval of frequencies in which the lower frequency is one-half the higher frequency (ref. V-1).

Intensity.- Ideally, sound intensity should be measured in terms of the displacement of air particles, their average velocity during oscillation, or the energy contained in their motion. At the magnitudes associated with ordinary sound, however, suitable techniques are not available for performing these measurements. Fortunately, the pressure changes in the sound wave can be determined with special pressure transducers or microphones. The dynamic pressure changes associated with sound differ by several orders of magnitude from static pressures normally encountered. Normal atmospheric pressure is about 10^5 N/m^2 (10^6 dyn/cm^2), whereas pressure fluctuations produced by sounds near the absolute threshold for hearing are on the order of 10^{-5} N/m^2 (10^{-4} dyn/cm^2).

For a simple sinusoidal wave (pure tone), pressure amplitude can be specified as the maximum value of the pressure increase above the ambient pressure or, alternatively, as the root-mean-square (rms) pressure. The relationship between these measures is

$$P_{rms} = \frac{P_{max}}{\sqrt{2}}$$

$$= 0.707P_{max}$$

where P_{max} is the peak pressure and P_{rms} is the rms pressure (ref. V-1).

The relationship in the equation refers to sinusoids. For complex waves (i.e., noise) which contain more than one frequency, there is no unique relationship between peak pressure and rms pressure. Peak pressure varies widely in a complex sound wave; rms pressure is more stable and is, therefore, the preferred measure when describing environmental sounds which usually contain many frequencies. Another reason for using the rms measure is that under specific conditions, the power present in a sound wave can be related to the rms pressure. Power in microwatts per square centimeter is given by

$$J = \frac{P^2}{10R}$$

where P is pressure and R is specific acoustic resistance (a quantity determined by the density and sound propagation velocity of the medium). As with sound pressure, the power associated with sounds one encounters in his everyday activities may vary by several orders of magnitude. Sounds that are of sufficient intensity to destroy the sensory cells of the ear produce as little power as 0.002 watt (ref. V-1).

The ear operates over an enormous range of sound intensities. The most intense sound pressures that can be received without producing damage are approximately one million times greater than the least intense sound pressures that can be detected. To conveniently deal with this range of physical sound intensities, a logarithmic scale is used. Because a logarithmic scale has no zero point, sound intensities must be specified with respect to some standard reference intensity. Sound intensity is commonly scaled as sound pressure level (SPL) in decibels according to the formula

$$SPL = 20 \log_{10} \frac{P_1}{P_0}$$

where P_1 is the pressure of the sound in question and P_0 is the reference pressure. One of the most widely employed reference pressures for sound measurement is $P_0 = 2 \times 10^{-5}$ N/m^2 (0.0002 microbar). This value is approximately equal to the lowest pressure change a young person with normal hearing can detect at a frequency of 1000 hertz. The relationship between decibels, microbars, and newtons per square meter is shown in table V-1 (ref. V-4). Common examples of representative SPL's are as follows.

TABLE V-1.- RELATIONSHIP BETWEEN DECIBELS, NEWTONS PER SQUARE METER, AND MICROBARS

[Adapted from ref. V-4]

dB	N/m^2	μbar
0	0.00002	0.0002
14	.0001	.001
34	.001	.01
54	.01	.1
74	.1	[a]1
94	1	10
114	10	100
134	100	1 000
154	1 000	10 000
174	10 000	100 000

[a]1 microbar = 1 dyn/cm^2.

Location	SPL, dB
A business office	50
Speech at 0.9 meter (3 feet)	65
Subway at 6.1 meters (20 feet)	95
Jet aircraft at 10.7 meters (35 feet)	130
Atlas launch at 45.7 meters (150 feet)	150
On gantry during Saturn V launch	172

For a complex (nonperiodic) sound, the pressure levels within various frequency bands can be measured, and a frequency spectrum can be constructed. The intensity of the total complex wave can also be specified with a single number, usually designated as the overall sound pressure level (OASPL). Equal weight is given to the frequencies between 20 and 20 000 hertz by the OASPL scale. (The OASPL scale is "flat" across this frequency range.) Several other single-value scales of complex sound intensity are in use. These scales apply different weights to the various frequencies. For example, the dBA scale gives more emphasis to the midrange of the audiofrequency spectrum. This scale approximates the ear's loudness response at relatively low sound pressure levels. The dBC scale is nearly flat across the audiofrequency range and is similar to the ear's loudness response at high sound levels (ref. V-1). Sound level meters in common use have filtering networks which allow determinations of A-weighted (dBA), B-weighted (dBB), and C-weighted (dBC) sound intensities as well as the previously described OASPL value. Sound power refers to the total sound energy radiation in all directions from a source per unit time. The power of sound sources is measured in watts and can be expressed by a logarithmic scale of sound power level (PWL) in decibels according to the formula

$$PWL = 10 \log_{10} \frac{W_1}{W_0}$$

where W_1 is the power of the source and W_0 is the arbitrary reference power of 10^{-13} watt (ref. V-5).

As sound waves diverge from a sound source in a spherical manner, the surface area of the wave front increases as the square of the radius. As a result, the energy per unit area decreases inversely as the square of the distance from the source. This is known as the inverse square law of intensity. A 3-decibel decrease in PWL (equivalent to a 6-decibel SPL decrease) occurs with each doubling of the distance from the source.

Duration.- Duration of exposure to a sound is critical when considering possible physiological or behavioral reactions. As will be discussed in later sections, brief exposure to a particular sound may be of no physiological consequence, whereas extended exposure to the same sound could result in irreversible damage. The effects of total duration also vary significantly if the sound is interrupted or if other parameters (e.g., spectral content) of the sound change during the exposure period.

Variations in sound pressure as a function of time may be represented as time-pressure histories. Such histories may be used to represent the temporal pattern of the pressure change directly as in the case of a shock wave or impulse noise. An impulse may be generally defined as an aperiodic pressure phenomenon of less than 1000 milliseconds duration, having a flat rise and decay time and a peak to rms ratio greater than 10 decibels. Common examples include the sound of gunfire and of drop forges. The occurrence of significant impulse noises during space flight is not likely; however, that such noise can occur in flight is exemplified by the thrusters on the astronaut maneuvering unit tested during the Skylab missions. These thrusters produced short noise bursts which peaked at 125 decibels SPL. The more typical sound to be expected during space flight is steady-state sound. Such sounds may be represented by time-pressure histories which specify the temporal change of an envelope within which a complex sound wave is contained. Potential sources of sound and noise during flight are briefly discussed in the following section.

Sources of Sound and Noise

Sound and noise problems may arise at several points during space operations. These problems can be broadly categorized into three general phases.

Launch and boost.- Noise sources during the launch and boost phases include primarily rocket engine noise during lift-off and aerodynamic noise developed during exit through the atmosphere. The duration of exposure for these phases is usually on the order of 3 to 5 minutes.

The external sound field of a space vehicle during launch and boost is created primarily by the booster rocket engines. When the vehicle and engine geometry, exhaust flow factors, and atmospheric conditions are known, it is possible to specify the noise at any point, both in the near and far field. Normally, this specification requires a determination of the total sound power produced by the rocket engine at each frequency, as well as details of how the sound is directed away from the turbulent exhaust flow. These results can then be used with the inverse square law of distance and atmospheric attenuation to describe the sound field at applicable points of interest. Allowance must also be made for refraction and reflection effects.

Because there are no large rotating or reciprocating parts in a rocket engine, the noise of rocket vehicles does not normally contain discrete frequency components. The level of very low frequency noise (1 to 100 hertz) produced by the turbulent mixing of the booster exhaust flow with the surrounding atmosphere generally rises as the booster increases in size and thrust. It is probable that very large superboosters of the future will produce their maximum noise energy in the infrasonic range (below 20 hertz).

As a space vehicle accelerates from its launch pad, lift-off noise can extend far into surrounding community areas but will quickly diminish within the crew compartments of the vehicle itself. With increasing airspeed, however, the crew compartments will be exposed to aerodynamic noise generated by boundary-layer turbulence. This boundary-layer noise reaches its maximum level as the vehicle passes through the range of maximum dynamic pressure and progressively decreases thereafter (ref. V-6).

Aerodynamic noise increases in level and peaks at lower frequencies as vehicles become larger. For vehicles in the size range of the Apollo spacecraft and greater, noise at maximum dynamic pressure tends to peak below 100 hertz.

On-orbit and interplanetary cruise.- During orbit and interplanetary cruise, vehicle internal sound and noise environments would assume special significance. As discussed in subsequent sections, noise can be a critical factor in safety, comfort, speech communications, performance efficiency, and emotional stability. Specific noise sources will in part be determined by mission requirements. However, some sources of noise such as fans, pumps, motors, and compressors associated with environmental control and waste management systems will always be present, as will be noise from communications systems such as intercoms and teleprinters. It is also probable that noise will be produced by the use of operational or experiment subsystems which contain moving parts or utilize compressed gases. Data that are representative of the noise environments to which crewmen were exposed during previous simulated and actual space flights are summarized in table V-2.

Entry and landing.- During entry, boundary-layer turbulence may again generate an internal sound field containing broadband noise of high intensity. The sound pressure levels reached may be comparable with those produced during the maximum dynamic pressure period at launch, but high intensities may be maintained for longer periods. Other noise sources such as those described previously may contribute to the internal vehicle sound field (ref. V-6).

Auditory Effects of Noise Exposure

Because the auditory system is the primary receiver of sound and is exceptionally sensitive to sound, it is not surprising that noise has its greatest effects on the ear and hearing. One set of auditory effects may become apparent after a noise of sufficient intensity has passed. These include temporary hearing loss, permanent injury to the ear, and permanent hearing loss. Other effects are noticeable while a noise is present. These include masking and interference with speech communication (ref. V-7). Each of these adverse auditory effects, as well as ways to protect against them, is discussed in the following subsections.

Ear damage and hearing loss.- Stimulation with very high intensity (135 to 170 decibels SPL) audiofrequency sound can produce gross destruction of auditory structures, including rupture of the tympanic membrane, separation of the middle ear bones (particularly at the joint between the incus and the stapes), and rupture of the fine membranes or sacs of the cochlea and labyrinth (ref. V-1). The primary site of auditory damage is the receptor organ of the inner ear, the organ of Corti, which contains the sensory cells (hair cells), nerve fibers, and supporting structures. Excessive exposure to noise

TABLE V-2.- REPRESENTATIVE NOISE DATA FROM SIMULATED AND ACTUAL SPACE FLIGHTS

Spacecraft	Mission duration, days	Measurement location	SPL, dBA	Octave band SPL, dB, for frequency, Hz, of -							
				63	125	250	500	1000	2000	4000	8000
[a]Apollo 2TV-1 command module	N/A[b]	Cabin, internal	65	45	48	58	55	61	58	62	55
[a]Apollo LTA-8 lunar module	N/A[b]	Cabin, internal	73	54	52	57	69	63	63	66	66
[c]Skylab Medical Experiment Altitude Test (SMEAT)	56	Wardroom	61	62	62	61	56	54	50	48	49
		Science pilot sleep compartment	54	61	58	56	52	46	43	40	41
		Experiment compartment	58	57	60	58	55	50	46	44	37
[d]Skylab 3	59	Wardroom	49	--	46	48	47	41	35	24	21
		Pilot sleep compartment	43	--	44	41	43	34	26	21	14
		Multiple docking adapter	61.5	--	61	56	55	53	52	47	45
		Airlock module	58	--	62	60	58	52	49	43	40
		Command module	57	--	61	56	56	52	49	43	41
[d]Skylab 4	84	Experiment compartment	55	43	47	46	56	48	36	31	32
		Pilot sleep compartment	41	46	41	38	41	34	25	16	9
		Dome hatch	52	50	53	51	53	47	41	36	28
[c]Spacelab Mission Simulation 3 (SMD-3)	7	Middeck	63	64	65	62	59	59	56	51	42
		Aft Spacelab	66	72	70	64	63	61	54	46	38

[a]Ground test (unmanned).
[b]Not applicable.
[c]Ground test (manned).
[d]Space flight (manned).

can lead to destruction of the hair cells. Other noise-induced injuries to the organ of Corti can range from mild distortion of its structure to collapse or complete degeneration. The auditory neurons may also degenerate. Once these specialized cells are destroyed, they do not regenerate spontaneously and cannot be stimulated to regenerate. Light- and electron-microscope studies have shown that high-frequency sounds produce damage within a limited area toward the basal end of the cochlea, whereas low-frequency sounds produce damage over a greater area toward the apical end of the cochlea.

An increase in hearing threshold level that results from exposure to noise is called a threshold shift. Threshold shifts may result from single or repeated exposures to noise. Also, as will be discussed briefly in a later section, threshold shifts can result from exposure to impulse noises.

Some threshold shifts are temporary and diminish as the ear recovers following the termination of exposure. Frequently, repeated exposures can induce threshold shifts that are chronic, though recoverable after the exposure ceases. When a threshold shift is a mixture of temporary and permanent components, it is a compound threshold shift. When the temporary component shift has disappeared, the remaining threshold shift represents irreversible damage and is permanent (ref. V-7).

Temporary threshold shifts can vary in magnitude from those causing loss of a few decibels in a narrow range of the spectrum to those causing temporary deafness. The time required for the ear to return to near normal can vary from hours to weeks. Noises with energy concentrations in the frequency range between 2000 and 6000 hertz appear to produce greater temporary threshold shifts than do noises elsewhere in the audible range. In general, A-weighted sound levels must exceed 60 to 80 decibels before a typical person will experience temporary threshold shifts even for exposures that last as long as 8 to 24 hours (ref. V-7). The greater the intensity level above 60 to 80 decibels and the longer the time of exposure to noise, the greater the temporary threshold shift. However, exposure durations beyond 8 to 24 hours may not produce further increase in the magnitude of the shift (ref. V-8). This factor has particular relevance with regard to long-duration exposures during space flight. Another property of temporary threshold shifts is that they are usually greatest for test tones one-half to one octave above the frequency region in which the noise that produces the shift has its greatest concentration of energy. Finally, temporary threshold shifts are less severe when an exposure has frequent interruptions than when an exposure is continuous.

People differ in their susceptibility to temporary threshold shifts. These differences, however, are not uniform across the audible range of frequencies. One individual may be especially susceptible to noises of low pitch, another to noises of medium pitch, and another to noises of high pitch. In general, women appear to be less susceptible to temporary threshold shifts from low-frequency noises than are men. This relationship is reversed for high-frequency noises (ref. V-7).

The hypothetical growth of threshold shifts after various single, continuous exposures to noise is presented in figure V-1. Certain facts are obvious from this figure. The more intense the noise, the more rapidly threshold shifts accumulate as the time of exposure to noise is extended. When the noise is only 60 decibels, a typical person has to be exposed for several hours before any significant threshold shift can be detected. However, when the noise is very intense (e.g., 120 decibels), a typical person exposed for only 5 minutes reaches dangerous levels of threshold shift. Combinations of intensity level and duration that produce threshold shifts greater than about 40 decibels are said to be in the region of possible acoustic trauma. In this region, the normal function of the auditory system may break down and permanent threshold shifts, or hearing loss, may occur after even one such exposure (ref. V-7).

Hypothetical recovery from threshold shifts after various single, continuous exposures to noise is illustrated in figure V-2. Although recovery processes are not well understood, it may be seen that complete recovery from temporary threshold shifts can occur within hours to a few days provided that the threshold shift is relatively small (less than 40 decibels) and the duration of exposure is short (less than 8 hours). Recovery from the temporary threshold shifts appears to be very slow when the initial shift exceeds 40 decibels, when the exposure duration exceeds 12 hours, or after long but intermittent exposure to noise. Recovery from very severe exposures may never be complete (ref. V-9). A definition of acceptable exposure limits is presented in the following subsection.

Exposure limits (damage risk criteria).- Considerable effort has been directed toward the establishment of criteria for maximum allowable sound exposure. This effort would be easier if there were a clear distinction between safe and potentially damaging sound exposures across the population. Unfortunately, as has been noted previously, individuals vary widely in their susceptibility to sound-induced hearing loss. This fact poses a problem in that if criteria are set low enough to protect highly susceptible persons, they would be excessively stringent for a majority of the population. Thus, the credibility of the criteria would be weakened. On the other hand, if criteria are set excessively high, susceptible individuals may suffer unnecessary hearing loss.

Short-duration limits: The most detailed and elaborate sound damage risk criteria for short-duration exposures published to date are those developed by the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) of the U.S. National Academy of Sciences National Research Council (NAS-NRC) (ref. V-9). Damage risk contours proposed by the CHABA group for periodic and nonperiodic sound exposures are presented in figures V-3 and V-4, respectively. The curves of figure V-4 indicate the noise levels at which one exposure per day is likely to produce damage. One-octave band sound levels are given on the left ordinate and one-third-octave and narrower band levels are given on the right.

The curves can be applied to particular band levels which may be present in broadband noise. For example, the bottom curve indicates that exposure to a one-octave band of noise centered at 3000 hertz with a level of 85 decibels

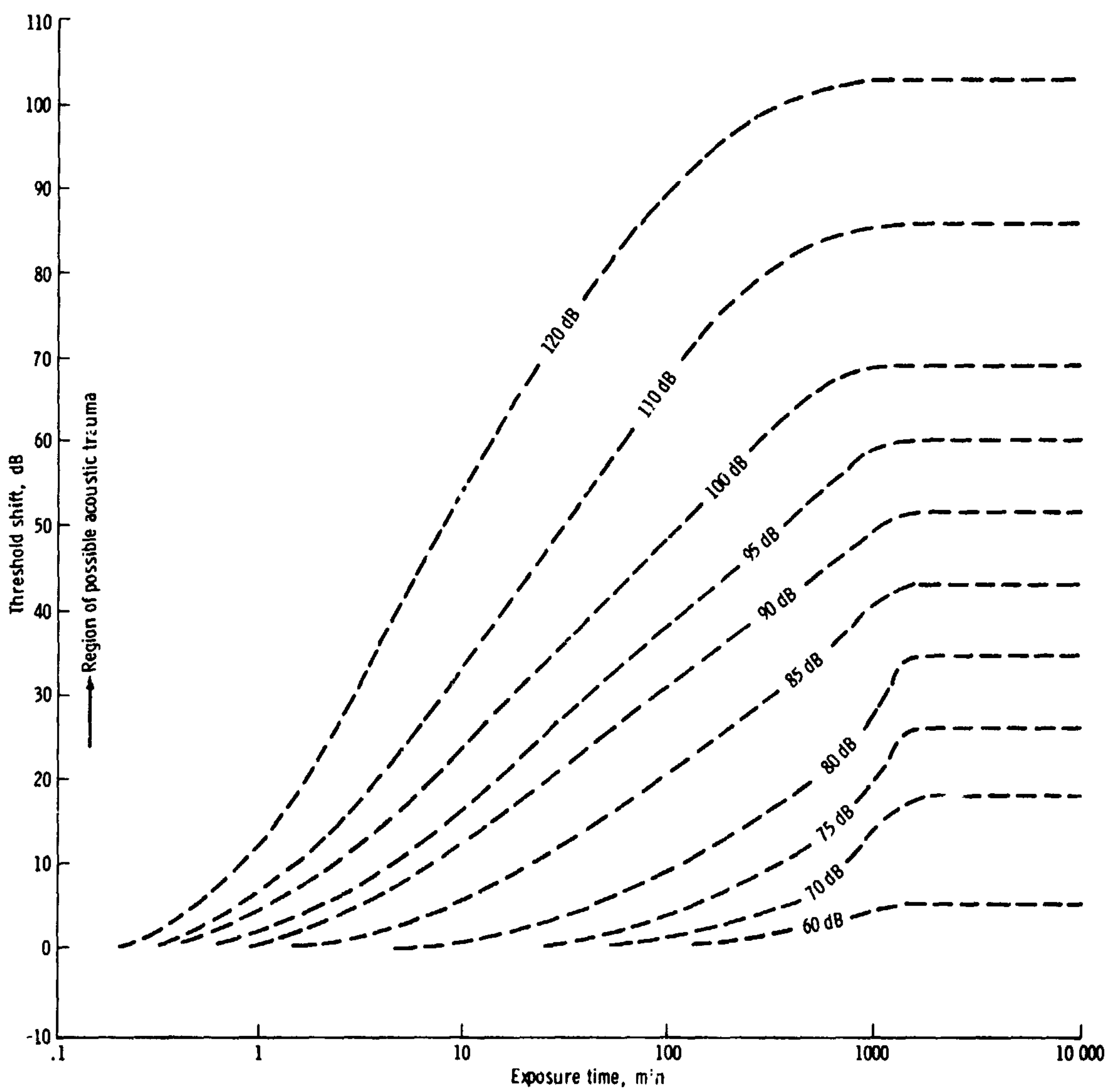

Figure V-1.- Hypothetical growth of threshold shift measured 2 minutes after single, continuous exposure to various levels of noise at a frequency of 4000 hertz. (Adapted from ref. V-7.)

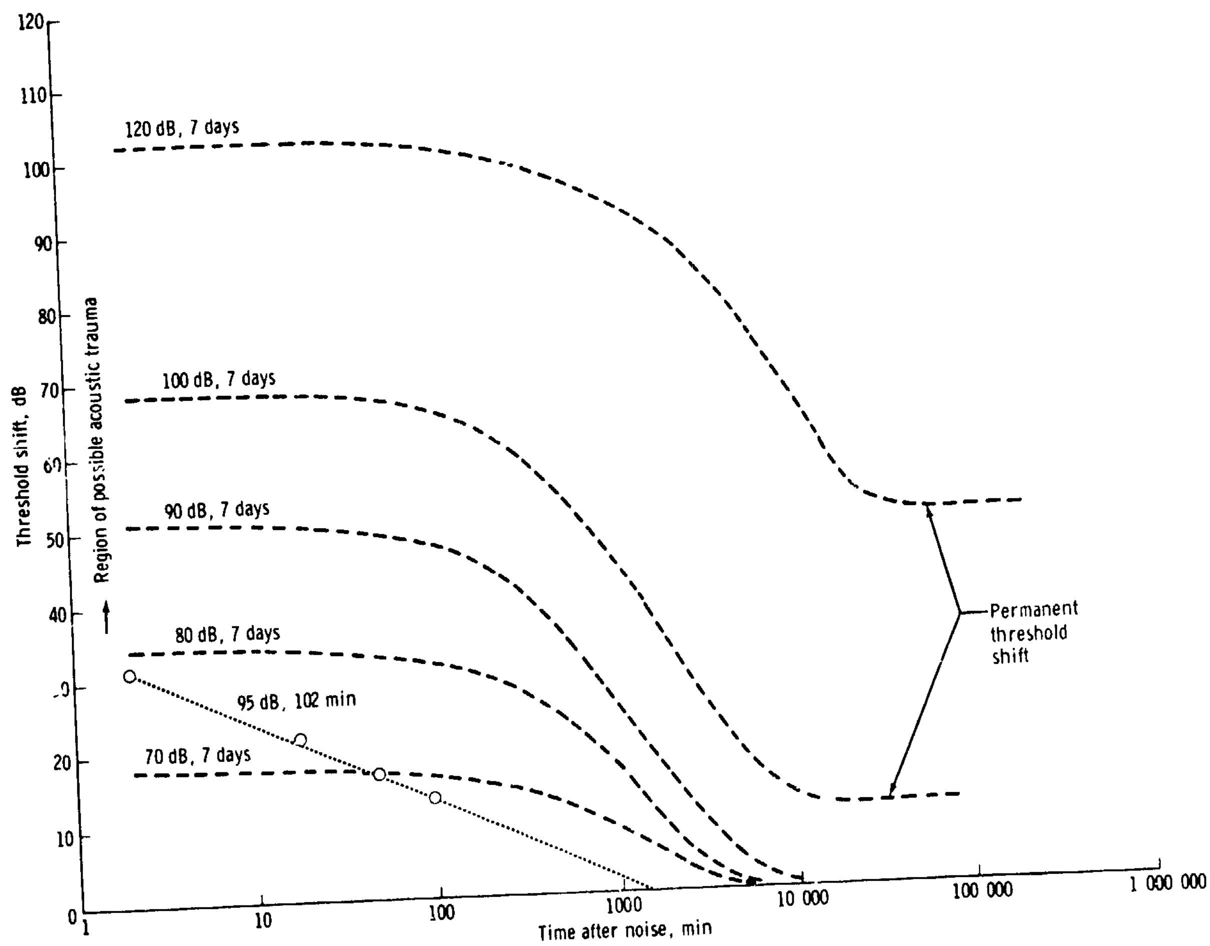

Figure V-2.- Hypothetical recovery from threshold shift after single, continuous exposure to noise of various levels and exposure durations at a frequency of 4000 hertz. (Adapted from ref. V-7.)

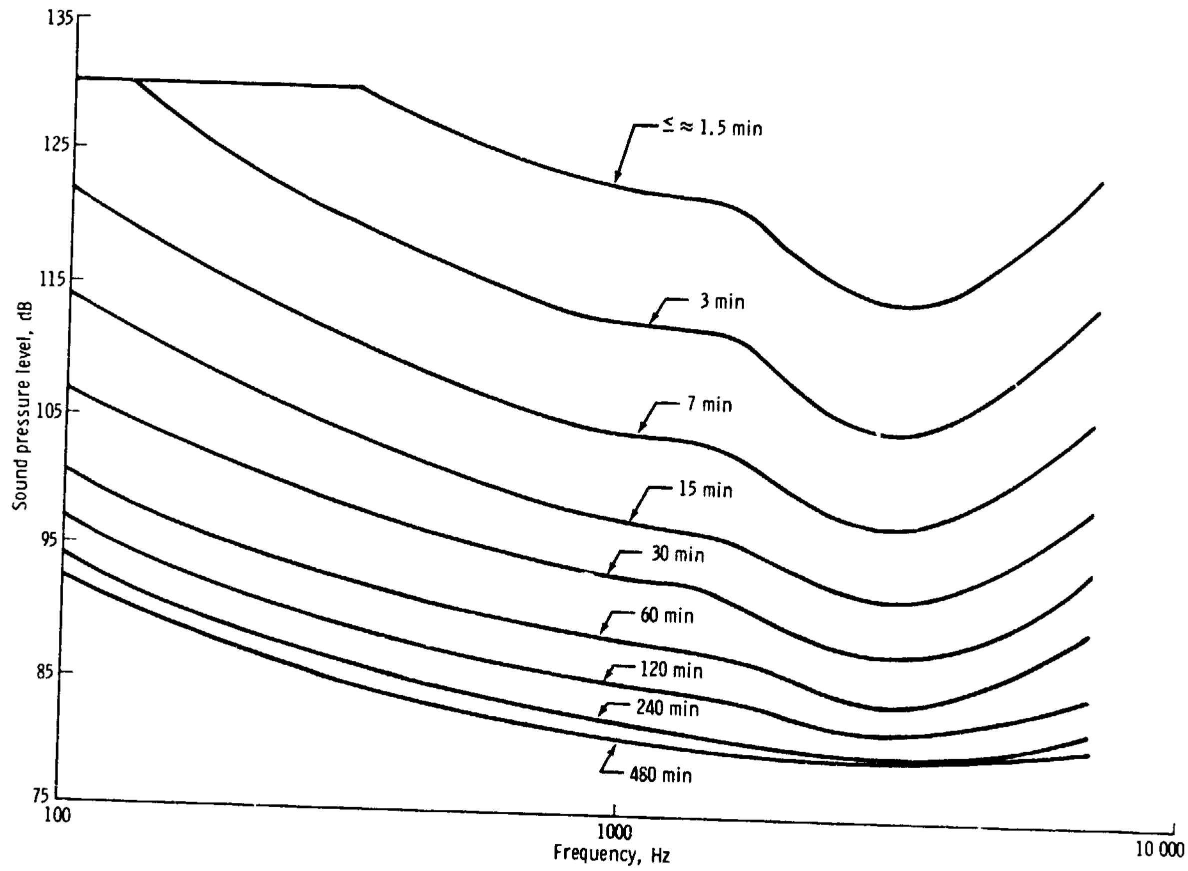

Figure V-3.- Damage risk contours for one exposure per day to pure tones of various durations; reference pressure is 2×10^{-5} N/m^2. (After ref. V-9.)

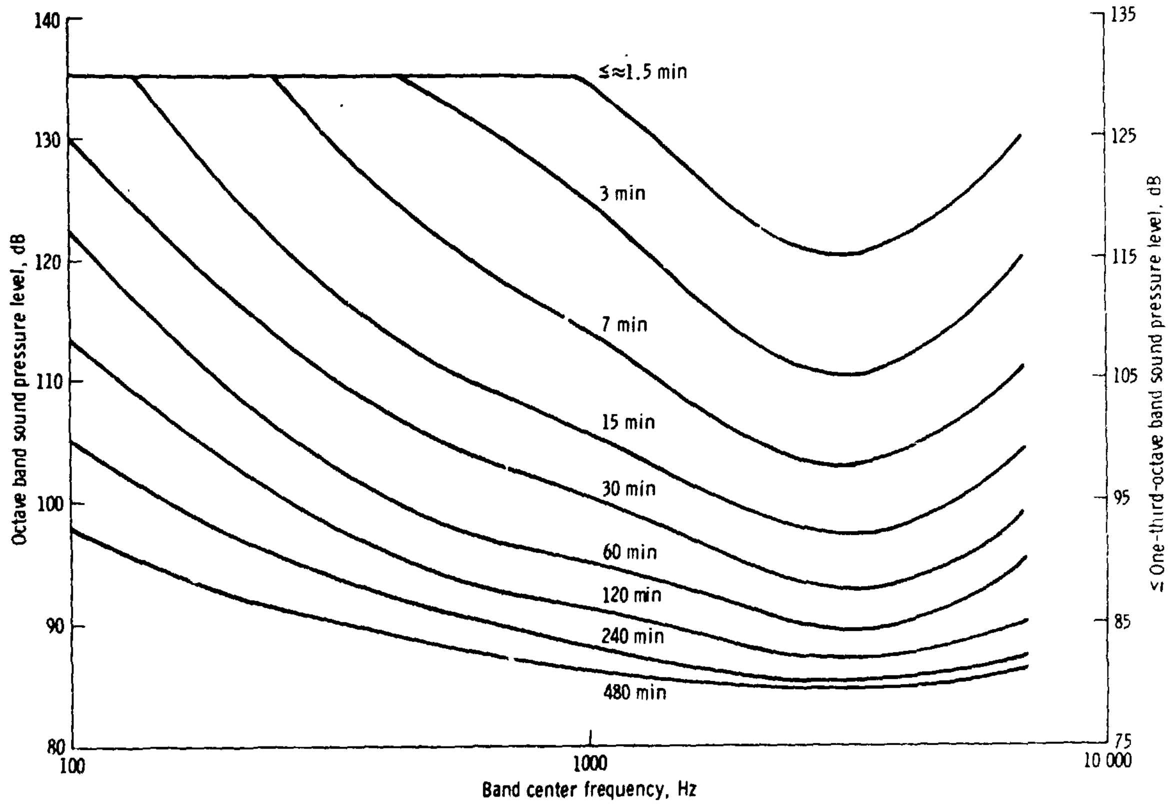

Figure V-4.- Damage risk contours for one exposure per day to one-octave and one-third-octave or narrower bands of noise of various durations; reference pressure for both scales is 2×10^{-5} N/m^2. (After ref. V-9.)

for 8 hours daily constitutes a potential threat to hearing. The curves of figure V-3 for pure tone exposures are interpreted in the same manner as the curves of figure V-4. These damage risk criteria have been incorporated into the design and procedure standard for acoustical noise[1] developed by the NASA Lyndon B. Johnson Space Center (JSC).

Damage risk criteria for impulse noise are not as extensive as the previously defined criteria for continuous (≤8 hours) noise. This deficiency results largely from the fact that the measurement of impulse noise is not as convenient or reliable as the measurement of continuous noise. Nevertheless, tentative limits have been established by the NAS-NRC CHABA (ref. V-10). An idealized impulse sound pressure waveform and exposure limits are presented in figures V-5 and V-6, respectively.

The damage risk criterion (ref. V-10) specifies acceptable exposure levels for two types of impulse waveform duration.

1. A pressure-wave duration, termed A-duration in the criterion, is the time required for the initial or principal pressure wave to reach its positive peak and return momentarily to ambient pressure. In the ideal pressure wave shown in figure V-5(a), the time duration is given by the distance on the time axis C - A.

2. A pressure-envelope duration, termed B-duration in the criterion, is the total time for which the envelope of the pressure fluctuations, both positive and negative, is within 20 decibels of the peak-pressure level. Included in this time is the duration of that part of any reflection pattern that is within 20 decibels of the peak level. In figure V-5(b), the B-duration is the time (D - A) + (F - E).

The damage risk criterion for impulse noise establishes acceptable peak-pressure exposure limits for a sound wave impinging on the ear at a normal incidence, as a function of either A or B pulse duration (fig. V-6). It is considered that below these limits (assuming 100 exposures per day), 95 percent of the exposed normal-hearing population will not sustain a temporary or a permanent threshold shift greater than 10 decibels at or below 1000 hertz, 15 decibels at 2000 hertz, and 20 decibels at or above 3000 hertz. Exposures that exceed any of the specified limits may be considered as potentially dangerous in the long term for the majority of exposed individuals.

Long-duration limits: The maximum allowable once-per-day exposure levels specified in figures V-3 and V-4 are especially applicable to defining exposure limits for rocket launch noise or other on-orbit mission phases where crewmen may occasionally be exposed to intense noise for brief periods. However, these criteria are inadequate with regard to the more typical

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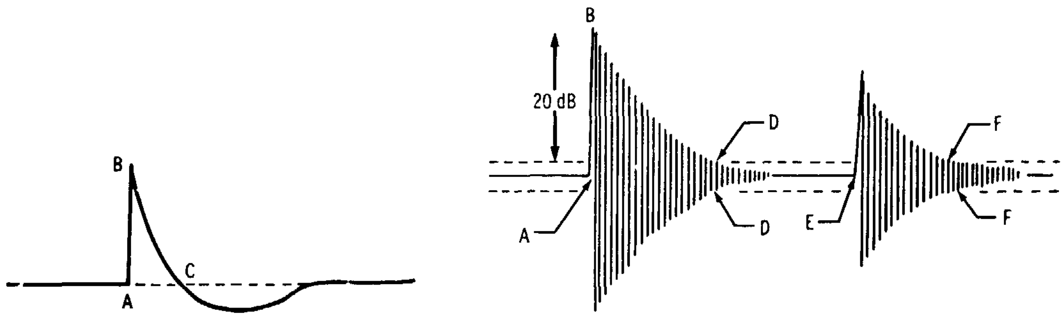
[1]MSC Design and Procedural Standard 145: Acoustic Noise Criteria. NASA Lyndon B. Johnson Space Center, Oct. 16, 1972.



(a) Type A-duration.

(b) Type B-duration.

Figure V-5.- Impulse waveforms. See text for explanation. (From ref. V-10.)

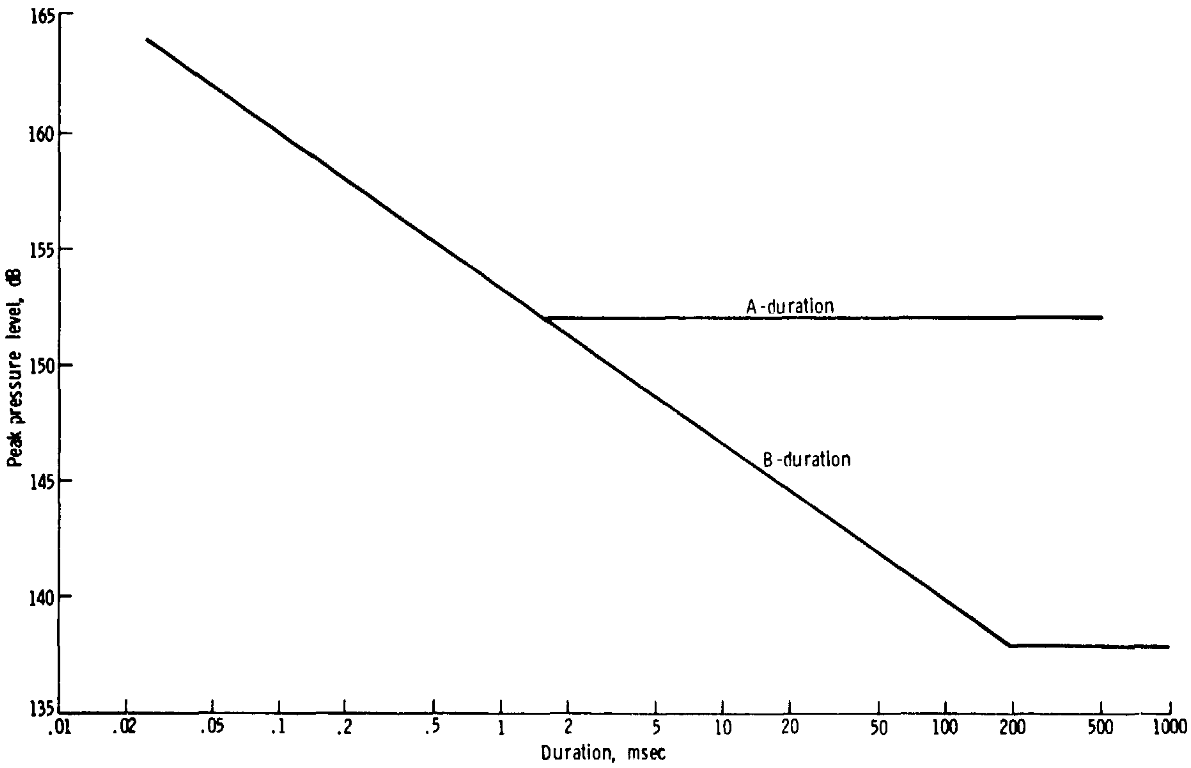


Figure V-6.- Damage risk criterion for impulse noise (gunfire); reference pressure is 2×10^{-5} N/m^2. See text for discussion. (From ref. V-10.)

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space-flight situation, in which crewmen will be exposed to noise continuously, 24 hours per day, for periods of 6 months or longer. A need clearly exists for valid standards which define safe limits for continuous, long-duration noise exposures.

Unfortunately, empirical data on which to base such standards do not exist. Therefore, it has become necessary to develop tentative long-duration exposure limits which are based in part on rational assumptions and on careful extrapolations from existing short-duration exposure data or "occupational health" audiometric data. To date, these long-duration exposure standards have been developed primarily for industrial and community noise applications; however, they can also be cautiously applied to the space-flight situation.

One approach that has been used in the past involves the use of noise criterion (NC) curves. These curves were originally developed primarily for defining acceptable workspace background noise where communications interference, loudness, or annoyance by noise are important design considerations. A family of NC curves is presented in figure V-7. It is significant to note that the JSC design and procedural standard for acoustical noise specifies that maximum allowable continuous sound pressure levels produced by normal spacecraft operating equipment or systems shall not exceed the NC-50 contour during work periods and the NC-40 contour during sleep periods. As evidenced by the Skylab orbital workshop (OWS) vehicle, in which sound rarely exceeded the levels specified by the NC-50 curve, these levels are conservative but not unrealistic.

Valid objections can be raised against the use of NC curves for defining allowable spacecraft noise levels. The primary drawback is that NC curves rarely, if ever, accurately represent the typical spacecraft noise spectrum shape. Although knowledge of energy distribution within the audible spectrum is important, it is more convenient and more meaningful in many instances to specify limits in terms of a single dBA value. Indeed, most noise criteria in use today do specify limits in dBA or some version thereof.

One of the most comprehensive and authoritative sources of noise level recommendations currently available is a report published by the U.S. Environmental Protection Agency (EPA) (ref. V-8). No attempt is made here to summarize the document; however, several of the recommendations proposed may be translated to space-flight noise environments. The EPA recommends that the level deemed necessary to protect hearing (with an adequate margin of safety) is a daily equivalent noise level L_{eq} of 70 decibels; L_{eq} is an energy average of A-weighted sound levels over a specified period of time. For reasonably steady sounds of the type anticipated on future spacecraft, L_{eq} is the average sound level meter reading utilizing the A-weighted network. (For purposes of comparison, it should be noted that NC ratings are about 5 decibels less than the measured dBA levels.)

The EPA determination of the 70-decibel L_{eq} value was based on the assumption that people would be exposed on a 5-day/week basis throughout their working lifetime of 40 years, that the noise would be intermittent rather than continuous, and that a period of relative quiet (60 dBA or less for 16

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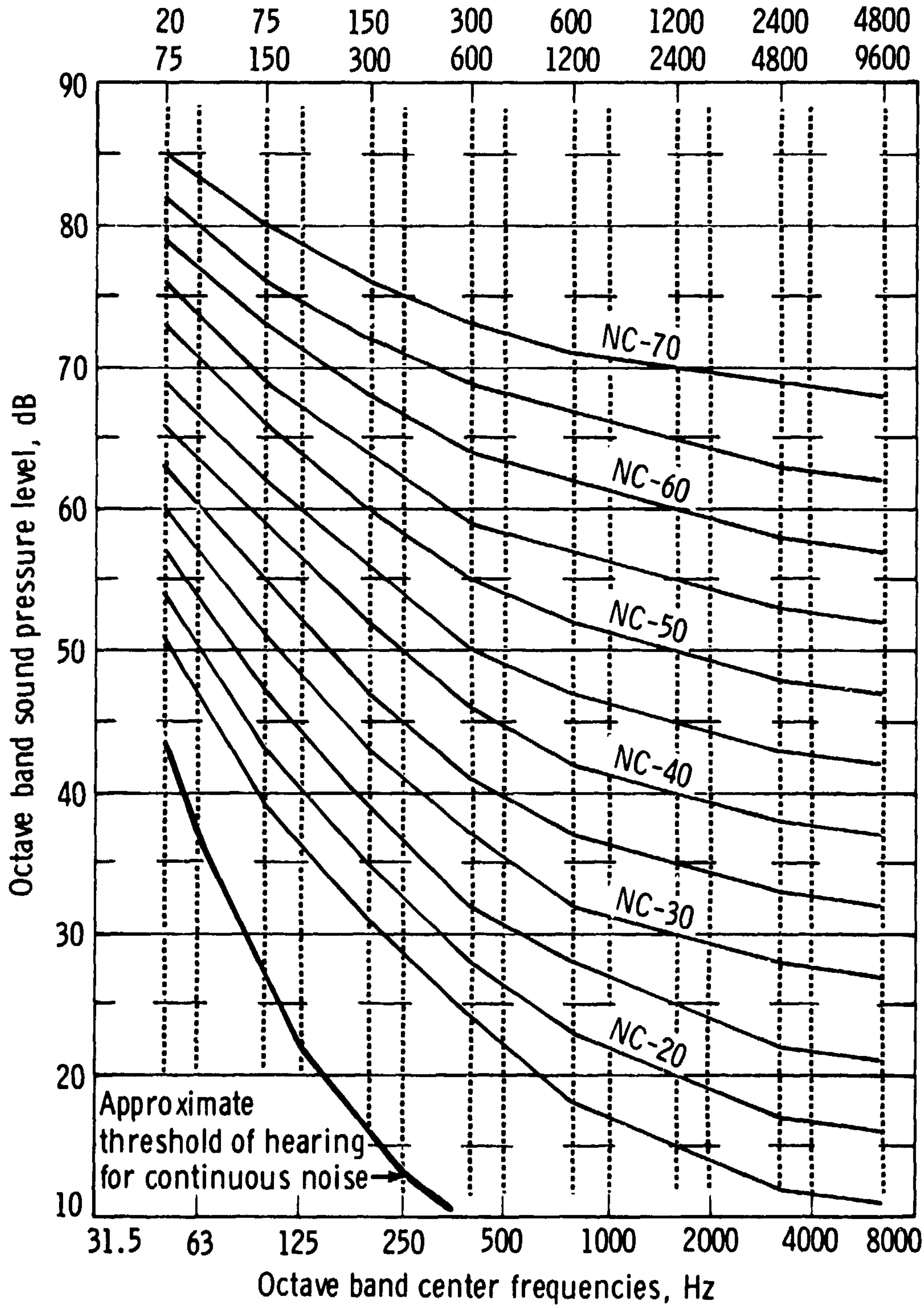

Figure V-7.- Noise criteria curves; reference pressure is 2×10^{-5} N/m^2. Lower abscissa consists of preferred octave bands; upper abscissa, of commercial octave bands.

hours) would occur after each workday to allow complete recovery from temporary threshold shifts. The EPA has also recommended correction factors to the 70-decibel L_{eq} figure to compensate for the effects of continuous noise exposures of 24-hour duration, as well as nonoccupational exposures of as long as 1 year rather than 40 years of occupational noise exposure.

Using the EPA data and recommendations, Bolt, Baranek and Newman (BBN), in a recent study conducted for JSC, determined that to prevent possible hearing damage during a 7- to 30-day Space Shuttle mission, the L_{eq} should not exceed 76 dBA.[2] This level is approximately equal (depending on the spectrum of the noise) to an NC value of 70. This level is considerably higher than the NC-50 value contained in the JSC design and procedural standard for acoustical noise. It must be remembered, however, that the JSC standard was written assuming exposures of indefinite length and considering such factors as communications interference and annoyance. The BBN recommendation of 76 decibels L_{eq} applies only to damage risk and is for a 7- to 30-day exposure. Indeed, BBN recommended that longer exposures require lower limits (e.g., 67 decibels L_{eq} for a 60-day mission; durations greater than 60 days were not addressed by the BBN study). Also, in the same study, BBN recommended that to minimize communications interference, sleep interference, annoyance, and performance decrement, the overall level on a 30-day mission should not exceed an NC value of 50 (approximately 55 dBA L_{eq}).

Prevention of ear damage and hearing loss.- The preferred approach to preventing ear damage and hearing loss is to ensure that people are never placed in a sound field that is potentially damaging. Ideally, the sound source itself should be reduced to acceptable levels if at all possible. Often, however, for a variety of practical reasons, this condition cannot be met. For example, noise levels to which flight crewmen or ground-support personnel may be exposed during the launch phase of a mission may be almost unavoidable.

Under such conditions, steps must be taken to prevent the sound from actually reaching the ear. At least three approaches may be considered. First, the person may be removed to a distance from the noise source such that spherical divergence and attenuation reduce the noise to an acceptable level. This approach has obvious limits as in the case of rocket launch noise. A second approach is to place a sound-attenuating physical barrier (e.g., wall or curtain) between the source and the receiver. The third, and often most practical, approach is to place a mechanical hearing protector over or in the ear canal to attenuate sound energy. The devices may take the form of ear inserts, which are available in several different types, ear muffs, and helmets. Of these three, a properly fitted ear insert generally affords the greatest protection. Even greater protection can be obtained when an insert and ear muffs are used in combination. Regardless of type, ear defenders are more effective in blocking high-frequency sound than low-frequency sound. It must be recognized that the maximum amount of hearing protection that can be obtained with any combination of devices is about

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[2]Pearsons, K. S.: Recommendations for Noise Level in the Space Shuttle. Bolt, Baranek and Newman Job No. 157160, Feb. 28, 1975.

45 to 50 decibels. Beyond this level, sound energy can be transmitted to the inner ear by bone conduction (ref. V-11). Ear protectors of any type must be properly selected and used. Despite the effectiveness of these devices, people often refuse or neglect to wear them for reasons of appearance, discomfort, and bother.

Aside from the devices described previously, it is noteworthy that the auditory system has a built-in mechanism to protect hearing. Sudden or unexpected sounds elicit a reflex contraction of the middle ear muscles which reduces the amount of noise conducted to the inner ear. Attenuation of as much as 10 decibels can be produced by this mechanism. This middle ear reflex is not effective in protecting against high-intensity impulse noise because the noise enters the ear before the reflex has time to occur.

Masking and Speech Communication

The masking phenomenon and the effect of noise on speech communication are discussed in the following paragraphs.

Masking effects.- Noise mixed with a signal (including speech) tends to raise the threshold for hearing that signal above the threshold in quiet. This phenomenon is called masking; the elevated threshold is the masked threshold. The masking effects of a pure tone, or of a noise with strong frequency components, differ somewhat from those of narrow-band and wide-band noise; however, all masking sounds possess several common features. The more intense the masking sound, the greater the effect. Low-frequency sounds (pure tone or noise) produce a greater masking effect than do high-frequency sounds of equal loudness. The masking effect is always greater above the frequency of the masking sound (refs. V-7 and V-11).

Speech communication.- Audible noise can adversely affect speech communications in several ways. First, as described previously, the noise can mask the speech signal. Second, the listener may suffer a temporary threshold shift as a result of the noise exposure and, consequently, higher than usual signal intensities will be required to accurately perceive speech signals. Also, noise may interfere with the efficiency of the total perceptual speech process.

Several different methods are available for predicting the consequences of noisy environments on speech intelligibility. Two of these are the speech interference level (SIL) and the articulation index (AI). Both methods have limitations. Under conditions of extreme noise masking, frequency distortion, and amplitude distortion, the predictive value of these methods breaks down. In such conditions, empirical speech intelligibility tests in the noise environment of concern (or an accurate simulation of that environment) become necessary. Nevertheless, these two predictive methods are widely used and will be briefly discussed. It is important to bear in mind that the articulation index should be used in all carefully designed speech communication systems. The speech interference level can serve as a rule-of-thumb guide in making some engineering decisions regarding face-to-face communications (ref. V-11).

Speech interference level: The speech interference level was designed primarily for use in situations characterized by noise having a relatively continuous spectrum. As such, the SIL is applicable to most spacecraft noise. The SIL is defined as the average sound pressure level in the three octave bands which are most important for speech communication. These bands are 600 to 1200, 1200 to 2400, and 2400 to 4800 hertz. More recently, the average sound pressure level of the octave bands centered at 500, 1000, and 2000 hertz have come into use. This latter calculation is referred to as the preferred speech interference level (PSIL). The SIL (or the PSIL) yields the maximum noise level that will permit correct recognition of 75 percent of phonetically balanced (PB) words and/or about 98 percent of test sentences. (This criterion is equal to an AI of approximately 0.5.) Consequences of selected SIL values on typical face-to-face communication are summarized in table V-3. It is also noted that for speech interference purposes, SIL values are equivalent to NC values. Thus, an NC-50 curve equals an SIL of 50 decibels.

Articulation index: An important advantage of the AI relative to other methods for assessing the effects of noise on communications is that the AI can be used for a wide variety of communication systems. The AI formulation is based on the fact that, to obtain high intelligibility, one must deliver a considerable fraction of the total speech bandwidth to the listener's ear and, also, that the signal-to-noise ratio at the listener's ear must be reasonably high. If the speech peaks are 30 decibels or more above the noise throughout the frequency band from 200 to 6100 hertz, the listener will make essentially no errors (AI = 1.00). If the speech peaks are less than 30 decibels above the noise in any part of the speech band, the listener will make some mistakes (AI < 1.00). If the speech peaks are never above the noise at all (ratio of speech peaks to rms noise less than 0 decibel), the listener will rarely be able to understand anything (AI = 0) (ref. V-11).

The AI can be established by one of two methods, the 20-band method or the weighted-octave-band method. In the 20-band method, the frequency spectrum between 200 and 6100 hertz is divided into 20 bands. The fractional contribution to the AI of each band is 0 to 0.05 depending on the difference (ratio) between the speech peak pressure level and the noise pressure level. The contributions made by the 20 bands when added together give the AI for the communication system in question. The weighted-octave-band method approximates the 20-band method and is computed from octave band measurements of speech and noise. Details on calculating the AI by either of these methods are available elsewhere (ref. V-11). The relationship between intelligibility and the AI for various types of speech materials is shown in figure V-8. Despite the utility of the AI, such factors as noise duty cycle, rate of interruption, frequency and amplitude distortion, reverberation, voice quality, and visual cues from the speaker must be considered.

Behavioral Effects of Noise Exposure

The behavioral effects of noise exposure in the areas of performance, sleep interference, and annoyance are discussed in this subsection.

TABLE V-3.- EFFECTS OF NOISE AS SPECIFIED BY SPEECH INTERFERENCE LEVEL ON PERSON-TO-PERSON COMMUNICATIONS

[From ref. V-11]

Speech interference level, dB	Person-to-person communication
30 to 40	Communication in normal voice satisfactory, 1.8 to 9.1 m (6 to 30 ft). Telephone use satisfactory.
40 to 50	Communication satisfactory in normal voice, 0.9 to 1.8 m (3 to 6 ft); raised voice, 1.8 to 3.6 m (6 to 12 ft). Telephone use satisfactory to slightly difficult.
50 to 60	Communication satisfactory in normal voice, 0.3 to 0.6 m (1 to 2 ft); raised voice, 0.9 to 1.8 m (3 to 6 ft). Telephone use slightly difficult.
60 to 70	Communication with raised voice satisfactory, 0.3 to 0.6 m (1 to 2 ft); slightly difficult, 0.9 to 1.8 m (3 to 6 ft). Telephone use difficult. Earplugs and/or ear muffs can be worn with no adverse effects on communication.
70 to 80	Communication slightly difficult with raised voice, 0.3 to 0.6 m (1 to 2 ft); slightly difficult with shouting, 0.9 to 1.8 m (3 to 6 ft). Telephone use very difficult. Earplugs and/or ear muffs can be worn with no adverse effects on communication.
80 to 85	Communication slightly difficult with shouting, 0.3 to 0.6 m (1 to 2 ft). Telephone use unsatisfactory. Earplugs and/or ear muffs can be worn with no adverse effects on communication.

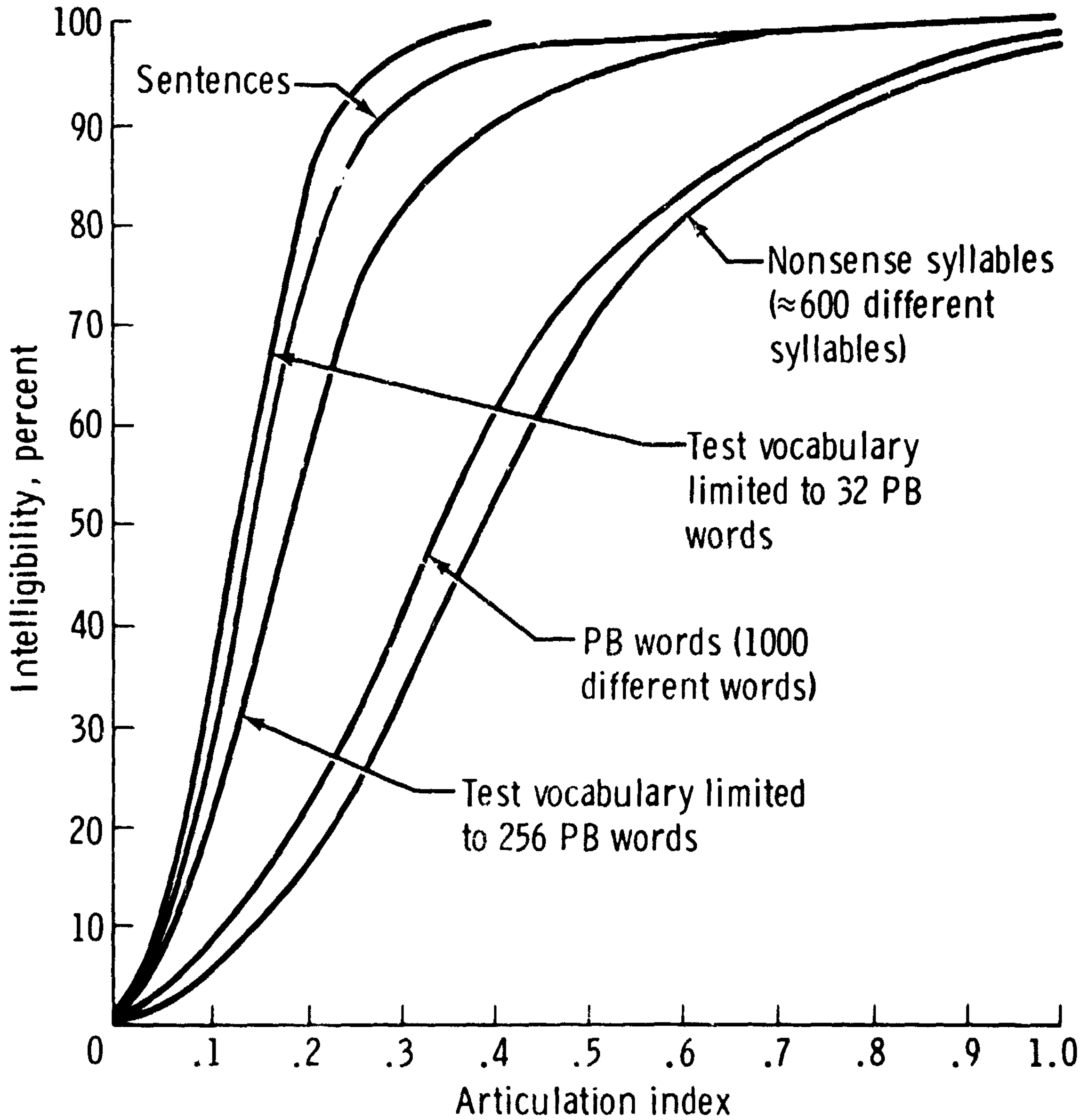

Figure V-8.- Relationship between the articulation index and the intelligibility of various types of speech-test materials. The relationships are approximate; they depend on such factors as skill of talkers and listeners. (From ref. V-11.)

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Performance.- The effect of noise on performance has been studied extensively in the laboratory and in actual work situations. Relevant findings from these studies are summarized in the following paragraphs.

When a task requires the use of auditory signals, either speech or nonspeech, noise at any intensity level sufficient to mask or interfere with the perception of these signals will interfere with the performance of the task. When tasks do not involve auditory signals, the effects of noise on their performance have been difficult to evaluate. Nonetheless, certain general conclusions have emerged.

1. Steady noises without special meaning do not seem to interfere with human performance unless the A-weighted noise level exceeds about 90 decibels.

2. Irregular bursts of noise are more disruptive than steady noises. Even when the A-weighted sound levels of irregular bursts are below 90 dBA, they may sometimes interfere with performance of a task.

3. High-frequency components of noise, above about 1000 to 2000 hertz, may produce more interference with performance than low-frequency components of noise.

4. Noise does not seem to influence the overall rate of work, but high levels of noise may increase the variability of the rate of work. There may be noise-induced pauses followed by compensating increases in work rate.

5. Noise is more likely to reduce the accuracy of work than the total quantity of work.

6. Complex tasks are more likely to be adversely influenced by noise than are simple tasks (ref. V-7).

Even when individuals are able to maintain high performance in noise environments, there may be a cost. This cost might include reduced psychological or physiological capacity to react to additional demands and increased fatigue after completion of the task. Many physiological and psychological responses to noise diminish or disappear when the noise is regular or predictable. Strategies can be learned so that the detrimental effects of noise on performance can be avoided. Under certain conditions, noise may even result in better performance because of such factors as auditory isolation provided by masking of other sounds by noise, greater activation and alertness of the worker, or paced performance when the noise is regular or rhythmic. Noises, however, often are not regular and predictable. Adaptation to noise is not always complete, and strategies to eliminate the adverse effects of noise are not always learned.

An ideal acoustical environment is one that does not disturb human performance either because of the properties of the noise itself or because of irrelevant messages carried by the noise. The task for the spacecraft designer is to eliminate disturbing noises while maximizing the chances that important, relevant messages carried by sound will reach the appropriate receiver.

Sleep interference.- The effects of noise on sleep are not well understood. It is known that the disturbing effects of noise on a sleeping person are related to several factors including the effective perceived noise level, the meaning of the noise to the person, the age of the person, and the stage of sleep the person is in. These effects have been measured in terms of altered electroencephalograph (EEG) activity and observable behavioral responses.

Empirical and anecdotal data also clearly indicate that noise can prevent a person from going to sleep or can awaken one from sleep if it is of sufficient intensity, has important meaning, or is of unusual character. Awakening may, in turn, cause a typical somatic arousal response which tends to alert the individual. The threshold of audibility or hearing of a noise may increase as much as 70 to 80 decibels as one goes from a light to a deep stage of sleep (ref. V-5). Noise above the level of audibility during a particular stage of sleep will usually cause some awakening, but the alertness or stress response may or may not occur depending upon the meaning or information value of the noise.

Some investigators have conjectured that because environmental noise can awaken a sleeping person or cause, without awakening, the changes in EEG activity that usually precede awakening, the noise is physiologically harmful, particularly to a person who is ill or recovering from undue fatigue. Data to substantiate such conjectures are sparse, even though there are data which clearly indicate that sleep deprivation can lead to harmful psychological and physiological effects (ref. V-5).

Individual variations of the effects of noise on sleep are great. Recent reviews of the literature in this area indicate that whereas some people may be disturbed at relatively low levels of noise such as NC-30 (35 dBA), others may sleep through levels equivalent to NC-80 (about 85 dBA). For this reason, the definition of acceptable and reasonable noise standards (limits) is difficult. Recommended levels for bedrooms and sleeping quarters have traditionally ranged from NC-25 to NC-40; however, because of practical design considerations, such levels may be difficult to achieve. (The JSC design and procedural standard for acoustical noise specifies NC-40 as an upper limit for sleep periods.) Nevertheless, that these levels are obtainable is exemplified by the Skylab OWS, in which noise levels in the crew sleeping compartments were at or below NC-40 (45 dBA) levels. In the Skylab environment, the crewmen's sleep appeared to be disturbed only by occasional intermittent noises.

In addition to the Skylab findings, several studies have been performed to evaluate sleep quality and quantity (sometimes with the aid of EEG measurement techniques) during simulated space-flight conditions. In these studies, noise levels ranged from 55 dBA (Skylab Medical Experiment Altitude Test) to

80 dBA (Lunar Module Noise Study). The EEG data obtained from the test subjects indicated little or no change in sleep patterns; however, intermittent noises (e.g., pumps turning on) did cause sleep arousals.

Until more definitive data are available, only general guidelines can be offered with regard to spacecraft noise limits for sleep.

1. The noise should be steady-state and preferably below NC-50 (55 dBA).

2. Intermittent noise sources should be eliminated.

3. Sleep areas should be acoustically isolated from spacecraft noise sources.

4. Provided the level does not exceed approximately 55 dBA, some steady-state broadband masking noise could be employed to alleviate disturbances due to intermittent noise. The level and/or spectral shape of this masking noise should be under control of the crewman.

5. Spacecraft designers should not assume that noise problems can be corrected by requiring crewmen to use hearing protection devices (earplugs or ear muffs).

Annoyance.- Various techniques for predicting potential annoyance caused directly or indirectly by noise exposure have been developed in the past 25 years. A large proportion of this effort has concentrated on annoyance evoked by aircraft noise, including the sonic boom. These techniques have also been used to assess the annoyance associated with a wide range of other environmental sounds.

One annoyance measure is perceived noisiness. This measure relates the noisiness of a particular environmental sound to the noisiness of a band of noise centered around 1000 hertz. The scale of perceived noisiness is PNdB. Details on the calculation of this value are available elsewhere (ref. V-12). Studies have shown that several attributes of an environmental sound, in addition to its loudness, affect this measure. Perceived noisiness increases with the duration of a sound, the "unwantedness" of the sound, the potential of the sound for speech interference, the degree to which the sound disrupts sleep, awareness on the part of a person concerning possible damage to hearing by sound exposure, and some special meaning that the sound might have for the listener (ref. V-1).

An almost bewildering variety of other methods has been devised to measure annoyance and social response to community noise or noise from particular sources such as aircraft. Some of these methods carry acronyms such as CNR, NNI, NEF, TNI, NPL, and CNEL. No attempt is made here to discuss these methods; they are mentioned only to underscore the disagreement, and seeming confusion, that exists in this area.

The annoyance (or, conversely, the acceptability) of sounds in future space-flight vehicles is more likely to be subject to individual variations than perhaps any other effect of noise exposure. As previously indicated, for speech requirements, the level of NC-50 has been widely recommended as an upper limit for such spaces as laboratories, drafting spaces, and engineering rooms. It, therefore, seems reasonable that the NC level required to provide reliable speech communication within a spacecraft environment should also provide a tolerable environment from an annoyance aspect. It should be noted, however, that the use of NC curves requires that the spectra be relatively uniform and contain no discrete frequencies or pure tones. Studies have shown that tones can be as much as 10 decibels more annoying than an octave band of noise of the same level. In other words, to be equally acceptable, a tone would have to be as much as 10 decibels lower in level than the octave band of noise. Correction procedures have been developed to account for this pure tone effect. These corrections are fairly complex and are not in full agreement. For purposes of space vehicle noise level recommendations, BBN has suggested that pure tones be reduced such that no octave band exceeds its adjacent octave bands on average by more than 3 decibels.[2]

Nonauditory (Physiological) Effects

Although considerable attention has been given in the past to the effects of noise on hearing, speech reception, performance, sleep, and mental well-being, only recently has noise been shown to produce potentially significant nonauditory physiological responses. Sudden, unexpected bursts of impulsive or steady-state noise will cause somatic (autonomic nervous system) responses in man and animals including changes in cardiovascular blood pressure and volume, breathing, pulse rate, gastrointestinal motility, endocrine gland excretions, and other neural and body activities. These responses are sometimes designated as arousal, and sometimes as stress responses, and are difficult to distinguish physiologically from responses that occur in emotional states such as fear or anger (ref. V-5). In the past, responses such as these were thought to occur only with relatively intense (e.g., >90 dBA) auditory stimuli. More recent data, however, suggest strongly that these physiological responses can occur at levels below those which produce auditory damage. The precise level at which physiological effects begin and the seriousness of these effects has not been determined, but it may be as low as 75 to 80 dBA (ref. V-3).

It is known that with continued exposure to noise, provided the noise connotes no harmful environmental condition or does not interfere with behavior as the result of auditory masking, man will adapt more or less completely; i.e., will cease to show arousal responses. Sudden noises will elicit an eyeblink response which, unlike the general somatic responses mentioned previously, does not habituate with continued exposure to noise.

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[2]Pearsons, K. S.: Recommendations for Noise Levels in the Space Shuttle. Bolt, Baranek and Newman Job No. 157160, Feb. 28, 1975.

In addition to the previously described types of somatic responses, other nonauditory responses to intense noise have been documented. For example, steady noise above approximately 110 decibels can cause some temporary and permanent (after years of exposure) changes in size of visual field, and noise above 130 decibels can cause nystagmus and vertigo (ref. V-5). However, these effects on visual and vestibular systems are found only with noise of sufficient intensity to cause, if exposures are continued for sufficiently long periods, permanent damage to the auditory system.

As indicated previously, additional research is required before limits can be establisl. ' for nonauditory physiological effects of noise exposure. However, as with the areas of performance, sleep, and annoyance, if spacecraft noise is limited to those levels (55 dBA) which permit satisfactory communications, then physiological effects should be transient and of no real significance.

Research Required to Refine Limits

Research required to refine limits in the areas of ear damage and hearing loss, communications, behavioral effects, and nonauditory physiological effects is discussed in this subsection.

Ear damage and hearing loss.- As previously indicated, a need exists to better define safe limits for continuous, long-duration noise exposure (i.e., exposures beyond 90 days and for periods of several years assuming manned interplanetary missions). Whether available occupational noise exposure limits will be applicable to the space-flight environment has not been fully determined. In this vein, a number of investigators have tentatively concluded on the basis of limited data that noise-induced hearing threshold shifts plateau after approximately 24 hours (refs. V-7 and V-8). If this supposition proves to be correct, then threshold shifts resulting from 24 or 24 000 hours of exposure to the same noise should be essentially the same. On the contrary, some limited data are available which suggest that temporary threshold shifts may increase in a nearly linear fashion with successively longer exposures to at least 600 hours (ref. V-4). Such conclusions have not been substantiated with valid test data.

Unfortunately, such data may not be easy to obtain. Ideally, these data should be obtained in operational situations or high-fidelity simulations in which individuals are exposed continuously to noise of known levels and spectra for long periods. Such studies are costly and it is improbable that they could be implemented for the evaluation of noise effects as such. Therefore, advantage should be taken of any opportunity to collect these data where men live and work in confined spaces for long periods. One such planned effort is to obtain internal cabin acoustical noise measurements during the early Space Shuttle flights.

Communications.- Acceptable levels for effective speech communication have been reasonably well defined. These levels are applicable regardless of mission duration. It should be cautioned, however, that if very long duration exposures do result in a progressive buildup of temporary threshold shifts (which would remain chronic as long as the exposure is maintained) or even permanent threshold shifts, then communications will be degraded because of the reduced ability of crewmen to accurately perceive auditory information. In this event, desired auditory signals would have to be increased in intensity to be heard.

Behavioral effects.- As previously stated, large individual variations exist with regard to the effects of noise on performance, sleep, and tranquillity. Because of this variation and because available data have been interpreted differently by different investigators, valid limits cannot be established in this area currently. As a first step to resolving this problem, it is recommended that all available information be carefully reevaluated with a view toward its specific application to the space-flight environment. If satisfactory conclusions cannot be reached, then additional research will be required. To be of value, such research should be performed with human subjects in a setting which matches to the greatest extent possible not only the types of acoustical but also the functional (including psychosociological) environments that may be encountered during space flight.

Nonauditory physiological effects.- Conclusions and recommendations for future research on the physiological effects of noise have been offered by a working group of the NAS-NRC Committee on Hearing, Bioacoustics, and Biomechanics (ref. V-5). These recommendations are applicable to research required to refine limits (physiological noise effects) for spacecraft and are as follows.

1. So-called stress reactions in humans, when continued for sufficiently long periods, can be physiologically harmful. However, it appears that the psychological and physiological responses to noise (excluding changes in hearing) are transitory and that they adapt out with continued exposure to the noise and, therefore, do not constitute harmful physiological stress. This conclusion is deduced from a relatively small amount of research and from incompletely tested concepts. For these reasons, research involving at least weeks or months of psychological and physiological testing with human subjects exposed, when awake, to quiet and to both low-level background and higher level intermittent noise is needed. Included should be further laboratory and field research on the effects of noise on sleep.

2. Physiological stress reactions that sometimes appear in certain noisy environments are likely to be the result of frustration or anger that occurs when the noise interferes with the reception of a wanted auditory signal or when the noise distracts from some other activity. Setting tolerable limits for environmental noise in terms of its subjective acceptability to people and its damaging effects on the inner ear would appear to provide levels of normally present environmental noise that are lower than those which can directly cause harmful nonauditory physiological stress conditions in man. It is recommended that laboratory studies be undertaken to study individual differences in sensitivity of humans to noise and to multiple stress conditions, including the performance of tasks requiring use of auditory cues and tasks not requiring such cues. Some real-life situations may be found in industries or in various societies that permit useful research studies in

this problem area; however, these studies must be undertaken with considerable caution because of the possible presence of conditions having effects that outweigh those the noise may have on the psychological and physiological conditions of the people involved.

3. Nonauditory physiological stress responses in an organism to normally present environmental noise are often the result of interactions between specific behavioral activities and the noise rather than the noise as such. Therefore, research aimed at understanding the nonauditory effects of noise on man should, under most circumstances, not involve lower animals.

NONAUDITORY SOUND

Definition and Description

As indicated earlier in this report, nonauditory sound is sound having energy at frequencies either above or below the normal audible spectrum. Ultrasound typically refers to frequencies above 20 000 hertz; infrasound refers to frequencies below approximately 20 hertz. Both infrasound and ultrasound have been demonstrated to produce physiological and behavioral effects. Sounds in both of these categories are likely to occur to some extent during future space-flight missions and, therefore, must be of concern to the spacecraft designer and the space physiologist. Observed physiological and behavior effects of nonauditory sound, as well as currently defined limits, are summarized in the following paragraphs. It will be noted that some of these effects are not unlike responses produced by exposure to high-intensity audiofrequency sound.

Infrasound

Noise spectra containing very low audiofrequency and infrasonic energy may excite body structures such as the chest, the abdomen, the eyes, and the sinus cavities. Under these conditions, subjects have reported chest wall vibration, mild respiratory alterations, gag sensations, blurred vision, and speech tremor. Auditory pain and tissue damage occur with high-intensity exposures. Ear pain occurs at levels on the order of 160 to 170 decibels at 2 hertz to 140 decibels at 50 hertz. Usually, such damaging effects can be prevented with properly fitted earplugs or ear muffs. At lower intensities, tickling sensations of the tympanic membrane and sensations of pr sure buildup in the middle ear have been frequently reported when ear protection devices are not used. Temporary threshold shifts occur which are a direct function of exposure intensity and duration. Responses indicating vestibular system stimulation have been observed following exposure to intense sound (135 to 140 decibels SPL) in the low audiofrequency and infrasonic range. Included have been observations of nystagmus, dizziness, nausea, and loss of balance. Behavioral effects stemming from some of these physiological responses include annoyance, discomfort, fatigue, and slower task performance rates (refs. V-1, V-4, V-6, and V-13). Limited data suggest that infrasound does not significantly affect speech reception. No data can be found regarding the effects of infrasound on sleep.

Research interests on the effects of infrasound appeared to peak during the 1960's, when researchers were concerned particularly about launch noise from the Apollo booster rockets. Since that period, little meaningful work has been done in this area. One study on the effects of infrasound on man is summarized in table V-4 (ref. V-13). Representative noises to which subjects were exposed in a series of tests are indicated on the left. Typical subjective reports associated with each of the noise exposures are listed on the right. These findings indicated that voluntary tolerance limits for frequencies below 100 hertz occurred around 150 to 154 decibels as determined by symptoms of nausea, giddiness, coughing, etc. The results of this study confirmed that the maximum permissible exposure to infrasound is approximately 150 decibels SPL. It should be stressed that the findings in table V-4 are maximum subjective tolerance levels. As previously indicated, various other effects of infrasound on man may occur at lower levels. In a recent review of the literature on infrasound, Von Gierke and Parker (ref. V-14) proposed a set of limits for long-duration exposure to infrasound (fig. V-9). These proposed limits, which are similar to a 24-hour exposure of 75 dBA, are based on extrapolation from a set of admittedly incomplete experimental data.

Ultrasound

Documented evidence of detrimental effects of airborne ultrasound on man are scarce, largely because ultrasound is especially amenable to noise control measures and atmospheric absorption. The proper use of hearing protection devices can eliminate most undesirable effects. Ultrasonic noise levels produced by several types of equipment and associated subjective responses of exposed individuals are summarized in table V-5 (ref. V-13). In this study, subjective complaints increased with increased noise intensities and exposure durations. Sensations of malaise and fatigue were experienced with levels as low as 90 decibels SPL. In interpreting the significance of the findings summarized in table V-5, it has been well established that many ultrasonic exposures also contain considerable audiofrequency energy. Often, it is this lower frequency energy that results in undesirable sensations and complaints. Eliminating or reducing the audiofrequency energy often eliminates the symptoms reported. Nevertheless, when airborne ultrasound exceeds the levels specified in figure V-10, subjective responses such as those in table V-5 may occur (ref. V-12).

The preceding findings and guidelines apply to airborne ultrasound. Structural or liquidborne ultrasound presents potential problems of a different nature. A large amount of energy can be carried in ultrasound vibrations. Direct contact of any part of the body with structures or liquids carrying ultrasonic energy will result in transmission of that energy to the body, where it is converted to heat. If the exposure is excessive, tissue damage resembling burns may result (ref. V-1). Ultrasound fields of sufficient energy to cause such tissue damage could conceivably be encountered

TABLE V-4.- HUMAN RESPONSES TO LOW-FREQUENCY AND INFRASONIC NOISE EXPOSURE

[Adapted from ref. V-13]

Exposure	Observed behavior
Frequency ranges	
0 to 50 Hz, ≤145 dB	Chest wall vibration, gag sensations, respiratory rhythm changes, postexposure fatigue; voluntary tolerance not exceeded.
50 to 100 Hz, ≤154 dB	Headache, choking, coughing, visual blurring, and fatigue; voluntary tolerance limit reached.
Discrete frequencies	
100 Hz at 153 dB	Mild nausea, giddiness, subcostal discomfort, cutaneous flushing; tolerance limit symptoms.
60 Hz at 154 dB, 73 Hz at 150 dB	Coughing, severe substernal pressure, choking, respiration, salivation, pain on swallowing, giddiness; tolerance limit symptoms.

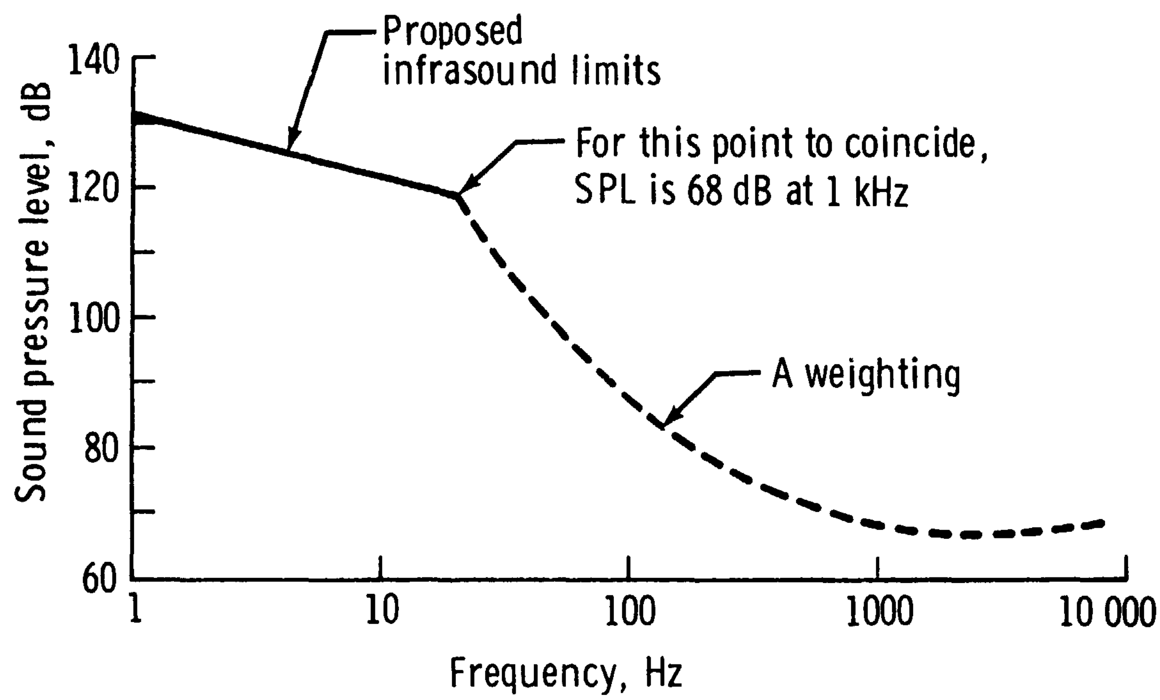

Figure V-9.- Proposed 24-hour infrasound limit, approximately equal to audio-frequency 24-hour limit of 75 dBA. Reference pressure is 2×10^{-5} N/m^2. (From ref. V-14.)

TABLE V-5.- SUBJECTIVE RESPONSES TO VARIOUS AIRBORNE ULTRASONIC EXPOSURES GENERATED BY ULTRASONIC INSTRUMENTATION

[From ref. V-13]

Item no.	Ultrasonic instrument type	Operating characteristics	Subjective response	Sound pressure levels, dB, at midpoint frequencies (third-octave bands), kHz, of -					
				10	12.5	16	20	25	31.5
1	Drill	Input freq. - 23.1 to 26.1 kHz, 400 mA	Pain in ears after few minutes. Headache after 1 hr. Nausea after 2 hr.	91	85	90	81	107.5	84
2	Welder	Input freq. - 15 750 Hz, intermittent exposure. On 15 sec, off 5 sec; 1 transducer	Malaise, backache; individual wore earplugs and symptoms disappeared. Operator had a cold when symptoms were experienced.	76	95	115	93	73	69
3	Cleaner	Input freq. - 20 kHz	Operator did not use the machine; the machine noise was too intense.	125	123.5	119.5	113	133.5	110
4	Cleaner	Input freq. - 40 kHz	Headache, malaise, fatigue; when necessary to use, the operator leaves the room.	77	78	79	96	77	77
5	Cleaner	Input freq. - 20 kHz, 1 transducer; water circulating at 293 K (20° C)	Fatigue and malaise. Shrill sound of 94 dB at 4000-Hz midpoint frequency.	81	78	84	93	76	76

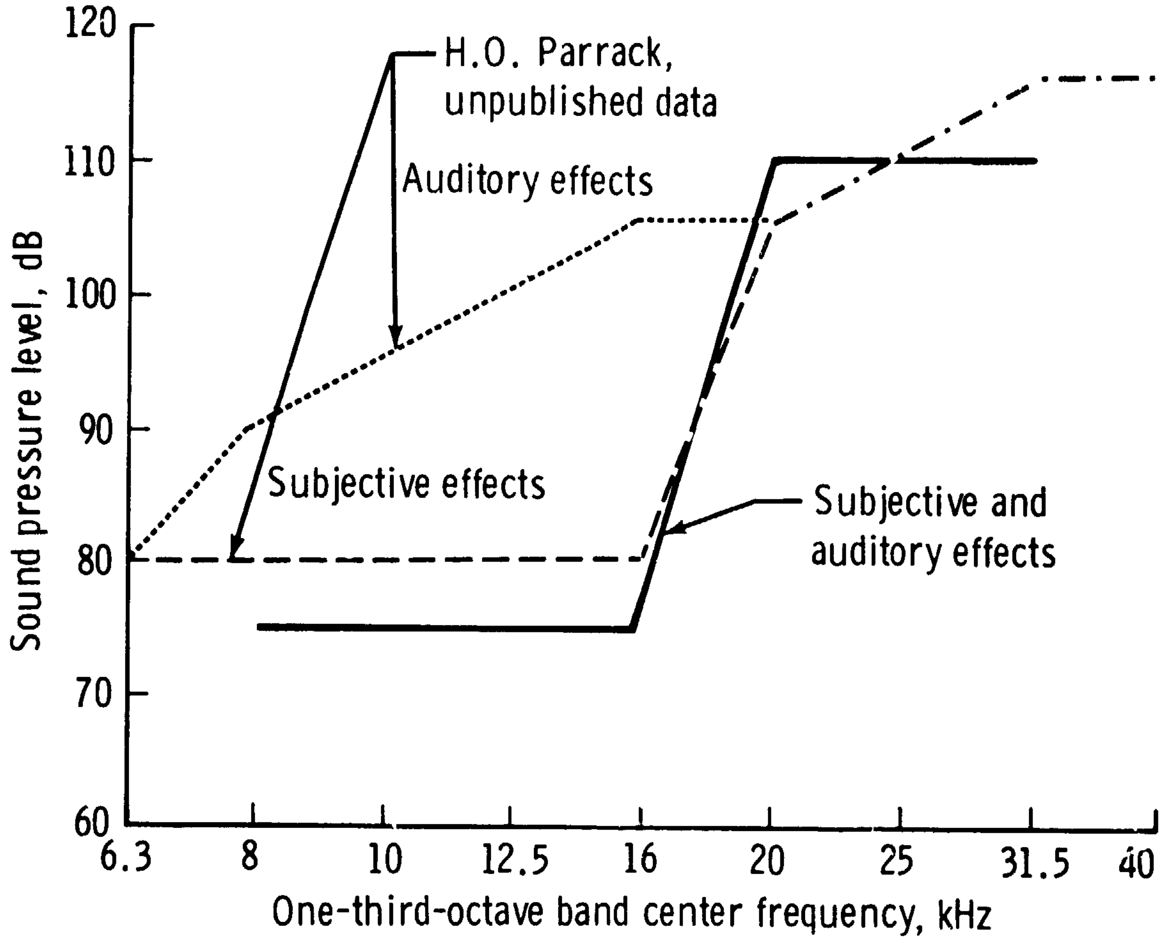

Figure V-10.- Proposed criteria for subjective and auditory effects of ultrasound; reference pressure is 2×10^{-5} N/m^2. (Adapted from ref. V-13.) The curve labeled "Subjective and auditory effects" (solid line) is from W. I. Acton, Institute of Sound and Vibration (ISAV no. 208), University of Southampton, Southampton, England.

in future space-flight environments. Limits for maximum allowable structural or liquidborne ultrasound are not available currently.

Research Required to Refine Limits for Spacecraft

Research required to refine limits for spacecraft is discussed in the areas of infrasound and ultrasound.

Infrasound.- It would appear that upper tolerance limits for short-duration exposures to infrasound have been reasonably well established. Data are sparse, however, with regard to long-duration exposure to lower level (75- to 100-decibel range) infrasound. Attempts should be made to acquire additional usable information in this latter area.

Ultrasound.- In general, on the basis of data available at the time of this writing, it would seem that the overall effects of ultrasound on man are not well understood. The literature must be more thoroughly evaluated. If sufficient data for the establishment of valid, safe standards for spacecraft design are not available, then appropriate research studies must be conducted.

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