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Chapter 9

NOISE AND VIBRATION [1]

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Noise and vibration have been undesirable byproducts of aviation from its beginning. An appreciable percentage of propulsion power has always been radiated as noise potentially disturbing to persons on the ground and transmitted inside vehicles to be received by passengers as airborne noise or structure-borne vibration. The large propulsion units of unprecedented thrust developed for manned space flight obviously raised questions about tolerability of the associated noise and vibration environments for crewmembers aloft as well as on the ground. Added to the noise and vibration impacts introduced by propulsion units, other phases of flight, such as reentry into the Earth's atmosphere, introduced phenomena of potential noise and aerodynamic buffeting, with which there had been little prior experience. Consequently, space efforts during a 15-year period (1958–1973) stimulated new research into human response to noise and vibration, to enable adequate planning and design to guarantee crew safety and performance capability, and avoid annoyance of exposed individuals and communities on the ground.

Airborne acoustic energy at sufficiently intense levels may interfere with routine activities, damage the auditory system, diminish the quality of performance, modify physiologic functions, and induce annoyance in exposed individuals and communities. The acoustic energy fields generated by aerospace systems are of intensity levels adequate to produce some or all of these adverse effects.

Mechanical vibration transmitted to human operators can degrade comfort and human performance. In some circumstances, vibration which is intense, prolonged, or repeatedly applied to man can affect operational safety and occupational health. The adverse effects of vibration may be immediate, developing as soon as the person is exposed to the stress (e.g., mechanical degradation of visual acuity by whole-body vibration); or the effects may be cumulative, being manifested only with passage of time under vibration stress or with repeated vibration exposure (e.g., fatigue effects on performance, vibration disease). The unifying field of bio-

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dynamics, stimulated largely by the urgent problems of manned space flight, has evolved to deal with the effects of all kinds of mechanical force on biologic systems.

Noise and vibration are two closely related phenomena, not only because of their common origin, but also because of their effects. As soon as airborne noise is transmitted from the air to the human body, it travels through the tissues as vibration, which in principle is not distinguishable from structure-borne vibration transmitted to the body. Vibration transmitted to any part of the body can be propagated through the tissues and received by the ear as sound and airborne noise, and if intense enough, can be felt as vibration by other body systems besides the ear. Thus, the mechanical characteristics of body tissue and the reception, transmission, and attenuation of vibration in tissue are of interest to human noise as well as vibration research. (These research areas overlap to some extent and are frequently treated under the same heading, as in this chapter.)

The first section is concerned with a comprehensive discussion of the noise factor in space systems. General characteristics of the physical stimulus of noise and corresponding psychologic and physiologic reactions of man are discussed. Space system noises are also considered, including special factors of infrasound, ultrasound, and impulsive sound and their effects on crewmembers, support personnel, and communities. Current practices of noise control from the standpoint of the source and receiver are discussed relative to specific aerospace system noises.

The results of vibration research obtained in support of the space efforts (also discussed) include physiologic and performance research, basic laboratory studies, operational tests, and evaluations of actual and simulated space missions. A new generation of vibration simulators evolved which could produce complex and random vibration in several degrees of freedom. Vibration capabilities have been incorporated into man-carrying centrifuges and into spaceflight simulators. The main emphasis in recent research, with such machinery, has been on man's short-term tolerance limits and his specific performance capabilities. The interaction of vibration with other spaceflight stressors such as acceleration, heat, noise, and radiation has also been studied. Finally, practical exposure criteria and protective measures in both the noise and vibration areas for various phases of space missions are discussed.

THE NOISE FACTOR

Nature and Characteristics of Acoustic Energy

Acoustic energy, a physical quantity, in space biology and medicine is generally considered from the standpoint of its undesirable effects on man. Physiologic and performance effects are related to descriptive parameters of physical exposure for interpretive as well as predictive purposes. Characteristics of the magnitude of the energy, the frequency components present, and the duration or time history of the exposure are primary determinants of human responses. To evaluate the impact of acoustic exposures on man, the nature and relevant parameters of the acoustic energy must be defined.

Sound

Sound waves are variations in the air pressure above and below the ambient pressure. Sound waves are described by the physical characteristics of intensity, spectrum, and the time history of the event.

Intensity. The intensity of the sound wave is determined by the amount its pressure varies above and below the ambient level. The wide range of pressures of interest to space biology and medicine is described by a logarithmic scale which expresses a ratio of sound pressure to a reference pressure in decibels (dB). The decibel is a unit of level commonly used to describe levels of acoustic pressure, power, and intensity; its scale is logarithmic expressing the magnitude of the ratio between two quantities.

Atmospheric or ambient level is measured in dynes/cm^2 (dyn/cm^2) or microbar (μbar) with 1 atm equaling about 1 000 000 μbar. The smallest periodic variation in ambient pressure (sound wave) occurring at a rate of about 1000 times/s can be detected by man at a pressure amplitude of approximately 0.0002 dyn/cm^2 or μbar or about

2×10^{-10} atm. This just detectable level was arbitrarily selected as the standard reference sound pressure for the practical decibel scale for sound measurement in gases in terms of sound pressure level (SPL). The relationship between sound pressure and SPL is shown in Table 1 with the more recently adopted reference of 0.00002 N/m². The intensity of a pressure (P), in terms of SPL is defined by

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

where $P_0 = 0.0002$ μbar and the SPL value is quoted as dB re 0.0002 μbar.

TABLE 1.—*Scales Commonly Used to Describe Magnitude of Acoustic Energy*

Sound pressure level (dB)	Sound pressure (μbar)	Sound pressure (N/m²)	Pressure (lb/in²)
174	100 000	10 000	1.47
134	1 000	100	14.7×10^{-3}
94	10	1	147.0×10^{-6}
74	1	0.1	14.7×10^{-6}
54	0.1	0.01	1.47×10^{-6}
14	0.001	0.0001	14.7×10^{-9}
0	0.0002	0.00002	2.94×10^{-9}

Spectrum. Sound waves of periodic (sinusoidal) oscillations in single or simple components are discrete tones, described in terms of oscillations per unit time or frequency, i.e., either cycles per second (cps) or hertz (Hz). Noises and complex sound are made up of many simple sounds distributed in frequency. Noises of concern to aerospace biology and medicine are frequency-dependent in terms of their effects on man; noise is commonly described in terms of levels of successive passbands of octave, half-octave, and third-octave bandwidths [5]. Spectrum is the plot of the various band levels as a function of frequency. The total sound pressure of a complex noise is expressed as overall sound pressure level (OASPL). Contributions of the various frequency bands of the spectrum are referred to as octave band sound pressure level (OBSPL), third octave band sound pressure level, and so forth.

The spectrum of acoustic energy which is important to man's perception ranges from small fractions of a single cycle to over 20 000 cps (Hz). The young, normal human ear is sensitive to energy in the range of about 15 to 20 000 Hz, which is termed the audiofrequency range. Energy at frequencies below about 20 Hz is subaudible sound or infrasound. Although the term ultrasound has classically been defined as acoustic energy above 20 000 Hz, the term is applied to energy ranging as low as 8000 to 10 000 Hz and above.

Time history. Pressure (sound) waves consist of rather specific individual patterns of fluctuations or changes in pressure with time that relate directly to the kind of source generating the pressure variation. Various types of sound waves are differentiated and identified by their time courses. Steady-state sounds are those with a time course or duration greater than 1 s. Impulse sounds, individual pressure pulses of sudden onset, are those with a duration of less than 1 s and a peak to root-mean-square (RMS) ratio greater than 10 dB. Impulse sounds are described by their rise time, peak level, and duration. The frequency content of impulsive sounds is determined by energy-spectral-density analysis. Pressure time histories describe variations in sound pressure of a signal as a function of time. The frequency content is not quantified in pressure-time histories of signals. Analytic techniques must be applied to the signal to obtain frequency or spectrum characteristics.

Propagation. Theoretically, sound waves in open air spread spherically in all directions from an idealized point source. As a result of this spherical dispersion, the sound pressure is reduced to half its original value as the distance is doubled, which is a 6-dB reduction in SPL. Sound propagation is further influenced by such factors as atmospheric attenuation, air temperature and turbulence, topography, and obstacles in the sound field. The general effects are those of propagation losses and distortion brought about by absorptive and reflective properties of obstacles encountered, scattering by irregular ground surfaces and meteorological turbulence, and shifting due to strong winds. The speed of sound in air is temperature-dependent and is about 344 m/s (1128 ft/s) at a temperature of 21° C (70°F).

Noises from aerospace sources do not radiate uniformly as from a point source but follow characteristic forms or patterns. This directivity of sound propagation from particular sources is considered in noise evaluations, to insure that exposure levels within noise fields have been adequately defined relative to placement of personnel and exposure of communities in the vicinity of the noise sources.

Aerospace Noises

Major sources of acoustic energy of concern in aerospace operations are vehicle propulsion systems and auxiliary equipment which provide maintenance support on the ground and mission (life) support on-board vehicles. The operational phases which must be considered are launch, orbit or cruise, and reentry. The manner in which acoustic exposure from various operations influences ground personnel, flight personnel, and other persons on the aerospace complex and in exposed communities must be defined. Relative energy levels and frequency content of noise exposures of various aerospace operations are shown in Figure 1.

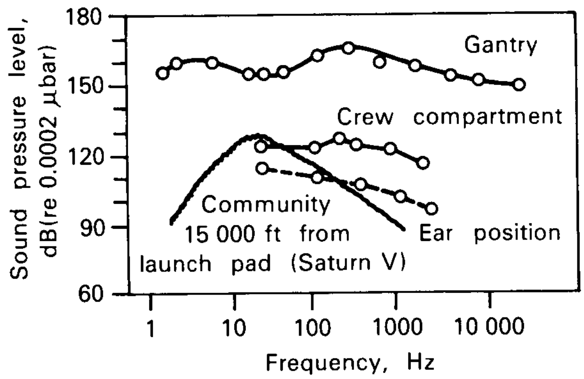

FIGURE 1.—Relative energy levels and frequency content of aerospace noises at launch [56].

Airborne noise is generated by propulsion systems, its magnitude increasing with the thrust of the engines. Jet and rocket noise have a continuous noise spectrum of random character, whereas propeller and turbine noise have spectra which are dominated by discrete frequency components determined by the number of blades and the speed of revolution (rpm). Aerodynamic or boundary layer noise occurs at high flight velocities through the atmosphere as a result of pressure fluctuations in the boundary layer rushing over the vehicle skin. Figure 2 shows the relative contributions of propulsion and aerodynamic noise as a function of time after ignition of a space rocket launch.

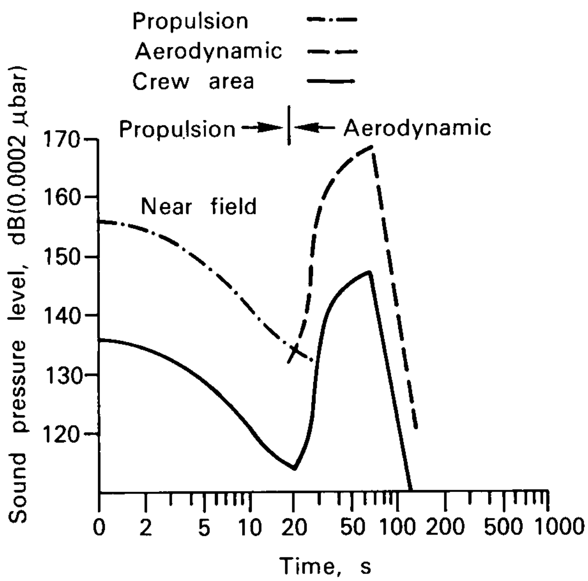

FIGURE 2.—Relative levels of propulsion and aerodynamic noise as a function of time after launch [32].

Jet noise from the propulsion system of a space vehicle predominates at launch and the zone of maximum intensity on the ground is in the form of a ring spreading outward from the launching pad. As the rocket gains altitude, the noise heard from below grows fainter and changes to a low-frequency rumble which extends far into neighboring areas and often disappears abruptly. Aerodynamic noise at the vehicle exceeds the propulsion noise with increasing flight speed but subsequently decreases as the vehicle progressively leaves the Earth's atmosphere. In the crew compartment, maximum noise exposures also occur after ignition from propulsion noise and as the vehicle passes through the range of maximum dynamic pressure (max q) from the aerodynamic or boundary layer noise. The overall sound pressure level time histories for an Apollo mission shown in Figure 3 were measured as a function of time from lift-off. The external noise levels are effectively reduced by the space-cabin structures and by the helmet-space-suit system as indicated by the relative levels at the crew station and at the ear. Aerodynamic noise is also encountered upon reentry of the capsule into the Earth's atmosphere. The levels of acoustic energy in the spacecraft cabin during reentry are comparable to those shown in Figure 3; however, the duration may be longer because of broader angles of trajectory and increased amount of time in the atmosphere.

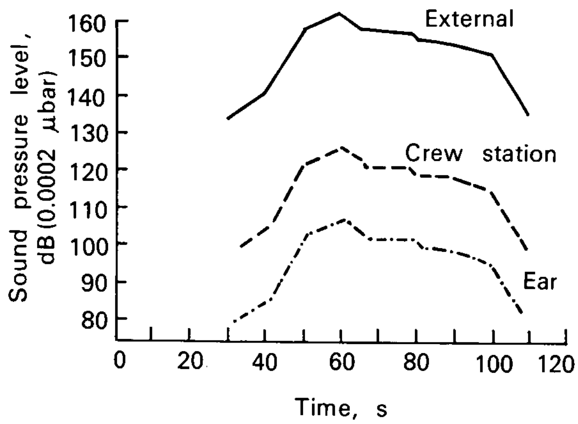

FIGURE 3.—Overall sound pressure level time histories as a function of time from lift-off of Apollo [32].

When supersonic speeds are reached by vehicles traveling in the atmosphere, shock waves or sonic booms are generated and propagated in a conical pattern behind the moving body [1]. If the flight angle relative to the ground is appropriate and if the pressure pulses are strong enough, the shock waves are perceived by observers on the ground as identifiable explosive-type sounds.

The magnitude or overpressure is arbitrarily defined as the positive peak pressure component of the pressure-time history of the sonic boom. During launch, the downrange flight angle and the altitude at which the downrange maneuver is executed largely determine whether or not the sonic boom reaches the Earth. Space activities, such as the US Space Shuttle Program in which pilot-controlled space vehicles will reenter the atmosphere at supersonic speeds and decelerate to accomplish a conventional landing, will also generate sonic booms. The nature of the reentry trajectories are such that large areas of the Earth's surface may be exposed to low-level sonic booms.

Primary noise sources are mission- and life-support systems during the orbital or cruise phases of space flight. The noise generated by several on-board systems during nonpowered flight is shown in Figure 4. The potential problems of continuous long-term exposure to moderately intense noise, as well as its influence on sleep and rest, were initially evaluated relative to spaceflight applications. Since that time, emphasis has been expanded to include man's important daylong exposures to all categories of noise in our present societies.

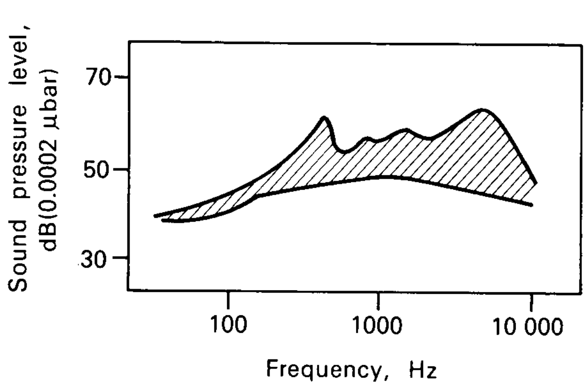

FIGURE 4.—Estimated range of noise exposure from on-board systems during cruise [56].

A significant characteristic of noises generated by space propulsion systems is the presence of very high levels of infrasound and low audio-frequency energy. As the exhaust diameter of such systems increases, the frequency at which the maximum acoustic energy occurs is lowered. The low and infrasonic energy is not effectively attenuated by the atmosphere; consequently, it is propagated long distances into adjacent areas

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and nearby residential and business communities. It is also more effective than higher frequency energy in causing structures to shake and rattle.

Airborne ultrasound, present around some aerospace propulsion systems, is effectively attenuated by the atmosphere and not propagated great distances. Adverse effects of airborne ultrasound have not been demonstrated for general outdoor conditions. Potential adverse effects of exposure to ultrasound on hearing and acceptability by individuals located close to ultrasound sources are discussed in a later section.

Pressure pulses of higher magnitude than those described as sonic booms accompany explosions, weapons fire, and the like, and are usually characterized as blast waves. Their magnitude and frequency spectrum depend on, among other variables, the explosive charge and distance from the source.

Effects of Noise on Man

The basic responses of persons influenced by space operations noises are broadly described as physiologic, those involving directly and indirectly physiologic mechanisms, and as psychologic, those which relate the basic attributes of sound to man's perception, judgments, attitudes, and opinions. In spite of this widely accepted dichotomy, in many noise exposure situations both elements are present, and the overall effects are mixed. The interactions of physiologic and psychologic responses to noise are too often ignored.

Physiologic Effects

Primary among the physiologic effects of noise is the response of the auditory system and the hearing function. Effects of acoustic energy have also been investigated relative to the vestibular system, mechanical stimulation of the body, autonomic nervous system, sleep, and startle. These latter effects, although described as nonauditory are, with few exceptions, also mediated through the auditory system.

Auditory response. The human auditory system is an extremely sensitive and highly specialized mechanism. The hearing threshold level or threshold of audibility is an individual's hearing sensitivity expressed in decibels relative to the normal threshold of hearing or standard hearing reference zero. The range of audible frequencies in the normal young human ear extends from about 15 to 20 000 Hz. The most sensitive region of the ear is from approximately 500 to 4000 Hz—the band most important for understanding speech. Infrasound, energy below the audible frequency range, is not detected by the human ear except at very high sound pressure levels. Harmonic components of intense infrasound may appear in the audiofrequency range at sufficiently high levels to be heard. Airborne ultrasound, i.e., acoustic energy above about 20 000 Hz, is not ordinarily perceived by the ear. An upper boundary of hearing is represented by the sound pressure levels at which tickle, ear discomfort, and pain may occur.

The auditory mechanism reacts in the presence of intense sound with a number of protective actions to reduce acoustic transmission to the inner ear [3]. At high intensities, the vibration of the stapes changes from a pistonlike movement to a rocking motion in the oval window due to subluxation of the ossicular joints. The stapedius and tensor tympani muscles contract also in response to appropriate loud sound, producing an increase in stiffness and possibly damping of the ossicular chain. The muscle reflex fails to provide protection from sudden and impulsive sounds shorter than about 15–20 ms because of its response latency which is nominally 25 to over 100 ms.

Acoustic stress. Excessive exposure to noise is a common cause of both temporary and/or permanent changes in hearing sensitivity or hearing loss. Temporary threshold shift (TTS) will return to normal or preexposure hearing levels within a reasonable time, whereas permanent threshold shift (PTS) does not recover, irrespective of time. Relationships have been established between noise exposure and TTS, and between PTS and noise exposure experienced daily over many years [73]. Noise-induced TTS is assumed to be an integral part of, and an essential precursor to, noise-induced PTS. Furthermore, it is assumed that without TTS, no PTS will occur. PTS also develops similarly to TTS but on a different time scale, and finally, all noise exposures which produce equal amounts of TTS are considered equally noxious with regard to PTS. These assumptions based on TTS data from the laboratory and TTS/PTS data from actual everyday noise exposures, have made it possible to formulate hearing risk criteria which relate noise exposure and hearing loss.

Excessive noise exposure may produce hearing loss associated with two general syndromes. Hearing loss may result from mechanical stress or damage in the tympanic membrane-middle ear system, or in the inner ear. A mixed syndrome reflected in both mechanical and sensorineural components in the hearing loss may result from intense noise exposures, particularly from those with impulsive characteristics.

Continuous and impulsive aerospace noise exposures may cause mechanical damage to the tympanic membrane and ossicular chain, and, in some instances, the inner ear as well. Hearing loss resulting from this mechanical type acoustic trauma is characteristically flat or about the same magnitude for all frequencies when there is no sensorineural involvement. Sensorineural hearing loss, if a result of an intense impulsive signal, may not be determined for several months after exposure because of the slow course of recovery.

Auditory pain due to noise is associated with excessive mechanical displacement of the middle ear system, and is believed to occur near the damage threshold. This pain, occurring almost independently of frequency at levels of 130–140 dB SPL and above, acts as a rather ineffective warning mechanism for overexposure. No pain is associated with overexposure of the inner ear which is often recognized only after inner ear damage has occurred and the hearing function has been adversely affected.

Continuous noise exposure may produce a slow, progressive loss of auditory sensitivity; this loss is first observed between 2000 and 6000 Hz with the greatest and most rapid decrease at 4000 Hz. The loss of sensitivity increases in magnitude and spreads in frequency with continued exposure. The manner in which noise-induced permanent threshold shift progresses with a number of years of exposure has been widely documented.

The susceptibility of individual ears to noise-induced hearing loss varies greatly, i.e., the amount of TTS produced by a specific noise exposure will differ markedly in each case. The capability of determining an individual's noise susceptibility prior to his assignment to a noise environment would be most valuable; however, despite considerable research, there has been no satisfactory method for arriving at such a decision. Exposure criteria have not incorporated a susceptibility factor because of wide variance from person to person and the inability to predict TTS for a specific ear.

Vestibular system. Subjective reports of disorientation, vertigo, nausea, and interference with postural equilibrium during high-intensity noise exposure suggest that intense acoustic energy may stimulate the vestibular system [13]. Empirical efforts to substantiate vestibular responses to noise have not been conclusive; however, this evidence does identify the vestibular system as the most probable site of acoustical stimulation [54, 107].

Sensory systems other than the vestibular receptors are clearly affected at levels above 140 dB and mechanoreceptors and proprioceptors may be the primary mediators of the physiologic response [71, 141].

General physiologic responses. The influence of noise on human physiologic responses other than audition is unclear, and consistent deleterious effects have not emerged. Changes in various physiologic indicators are measured under laboratory conditions and in real-life situations; however, the magnitude of changes are frequently no greater than those experienced in daily living activities. In addition, physiologic responses which accompany individual noise exposures are frequently transitory. Generally, humans adapt very well to stimuli such as noise; however, questions yet to be answered concern possible adverse effects on health and well-being due to regular long-term exposure to noise over many years. Neither long-term adaptation to noise nor the manner in which widely varying individual differences affect physiologic reactions are well understood.

General and specific physiologic responses to sound have been measured by a number of investigators [19, 65, 68, 69, 141]. The results are complementary and include effects on peripheral blood flow, respiration, galvanic skin response (GSR), skeletal muscle tension, gastro-intestinal (GI) motility, cardiac response, EEG, pupillary dilation, renal and glandular function. Many of these response changes have been reported at relatively low sound pressure levels (70–90 dB).

Studies of nonauditory effects in industrial settings suggest that noise does influence general health. According to Kryter [72], Andriuken has reported greater arterial blood pressure in workers exposed to high-frequency lathe noise and to very intense broadband noise found in ball bearing production shops than in men working in less intense noise. Shatalov et al [120] showed differences in various cardiovascular responses of persons who worked in a spinning mill noise of 85–95 dB compared with those who worked in 114–120 dB of industrial noise. The incidence of symptoms of vascular disorders, cardiac arrythmias, and pale, taut skin conditions were higher in employees who worked in noise levels greater than 90–95 dB than in those working in less intense exposures [67]. Subjective reports of fatigue, loss of appetite, irritability, nausea, disorientation, headache, and even inability to remember, continue to be reported as a result of noise exposure.

Numerous other factors in industrial noise situations where physiologic problems have been observed indicate that caution must be exercised in attributing adverse effects solely to noise. An apparent corollary indicates that as noise exposure in work situations increases in intensity, other elements of the same environments, considered stressful to physiologic functions, increase correspondingly. The contributions to physiologic problems of temperature extremes and poor ventilation, threat of accidental injury or death, demands of specific tasks, and other nonnoise factors which tend to grow with intensity of noise exposure cannot be ascertained without being controlled in test populations.

Sleep interference. Interference with sleep due to noise may be a serious effect, for there is widespread agreement that adequare sleep is a physiologic necessity. There are two general aspects of sleep interference due to noise: actual arousal or wakening, and changes within the sleeping individual who does not awaken to the noise. Sleep is in stages or levels, which are revealed by patterns of electrical (EEG) activity of the brain. In terms of arousal, individuals are more resistant to noise stimuli during some stages of sleep than others. During sleep stage 2, subjects are more susceptible to behavioral awakening than during the other stages; they are most resistant during stage 4 and REM (rapid eye movements, with dreaming) sleep. Recent work by Lukas and Kryter [83] indicates an age factor in sleep interference due to noise. Aircraft noise and sonic boom-type stimuli perceived in the home environs awakened older persons (67–72-year-old males) about 70% of the time, younger persons (21–22-years-of-age) less, and children (5–8-years-of-age) hardly at all. Williams [138] reports the threshold for behavioral wakening has been measured at only 20 dB or thereabouts above the hearing threshold of audibility, while Kryter reports awakening thresholds of 30 dB in stage 2, and 50 dB in stage 4.

Sleeping individuals not awakened in response to noise stimuli have nevertheless shown changes in peripheral vasoconstriction as well as in EEG. Finger pulse amplitude changed at noise levels 15 dB below arousal threshold, and heart rate changes were measured at 10–15 dB below arousal threshold. These responses confirm that measurable effects of noise on biologic responses in man during sleep are observable even though the sleeper is totally unaware of the acoustic exposure.

Myasnikov [100] describes an interesting investigation of sleep in which subjects experienced broadband continuous noise exposure of 75–78 dB during simulated space flight. A dichotomy emerged: those who fell asleep rapidly, slept well and awakened feeling well; those who fell asleep with difficulty, did not sleep well and did not feel well on awakening. Other effects were generally bimodal corresponding to the two types of sleepers. The author concludes that selection of candidates for astronauts or cosmonauts should include screening of sleep characteristics to eliminate poor sleepers.

Startle. Startle may be evoked by a wide variety of stimuli but is particularly susceptible to sudden, unexpected noises. The physiologic aspects of the startle response are not specific to the stimulus. They include increased pulse rate, increased blood pressure, and diversion of blood flow to the skeletal musculature. Startle responses are not known to have a direct adverse physiologic effect on personnel. They do not occur frequently in everyday life and generally are not considered to constitute a widespread problem.

Psychologic Effects

Psychologic responses to noise of interest to aerospace biology and medicine are potential problems in voice communication and crewmember performance.

Voice communication. The technical discussion of voice communication which follows, based largely on research and experience with standard American English, may not be directly appropriate for non-English languages. Processing different languages by a common space-communication system may be of concern as international cooperation in aerospace medicine and biology increases. Factors which influence operational voice communication have been systematically examined as a function of language. The statistics of language may vary significantly from one to another, and communication capability may likewise be differentially influenced. Voice communication as a function of language, although essentially ignored to the present, requires further definition in future aerospace research activities.

Speech communication may be adversely affected by noise exposures in two basic ways: the speech signal may be masked or drowned out by the noise, and/or temporary hearing loss due to the noise exposure may reduce the individual's ability to understand messages. Temporary hearing loss, if it occurs in this situation, is highly variable and cannot conveniently be included in schemes for estimating or predicting voice communication efficiency in noise. Masking effects of noise on speech communication, which are well understood, form the basis for quantitative predictive schemes and criteria. These criteria do not include low-frequency and infrasonic exposures. The extent to which such exposures affect the prediction of speech intelligibility has yet to be determined. Subaudible airborne sound is effective in eliciting body vibrations and responses, which, as they are reflected in speech production, may prove a problem.

Influences on voice communication have been categorized by Webster [136] as environmental, personal, message, and equipment. Noise, both acoustical and electrical, is the predominant environmental factor responsible for masking and degrading speech. Conditions of whole-body vibration and of artificial atmospheres such as $He-O_2$ mixtures have demonstrated clear-cut influences on the speech communication process [106]. Combined stresses, i.e., noise and vibration, may produce greater decrements than those found in either element experienced singly. Task requirements, possible danger, other health effects and stresses may also cause communication to deteriorate.

Personal factors are concerned with the manner in which the speech message is produced and perceived by the individual. Poor speech production habits, regional and national dialects, and word usage are important. Hearing loss, either temporary or permanent, will also degrade perception. Experience in the communication environment facilitates efficiency as does an adequate program of training concerned with the environment in which the trainee will perform and the speech materials and equipment he will use.

Type of material or messages which result in reduced intelligibility involve large vocabularies, unexpected terms, and phrases used infrequently. Equipment degradation of speech can be effectively engineered out using principles such as noise-cancelling microphones, microphone noise shields, adequate passband of the system, appropriate peak clipping, low impedance characteristics, and the like. Most communication systems using these principles account for very little speech degradation. Engineers, to insure a successful design, must know characteristics of the system and the manner in which the system is to be used.

Various procedures are in widespread use for analyzing and predicting the effectiveness of electronically aided (headset) and face-to-face speech communication in noise. These procedures involve a physical description of the noise exposure in both level and spectrum, a nominal or measured speech level and spectrum, and an analytic procedure based upon experimental data relating masking effects of noise to speech reception and a descriptor of expected efficiency of speech communication as a function of the noise. The least sophisticated and easiest to use method is the A-weighted sound pressure level (dBA). Speech Interference Level (SIL or PSIL) is the simplest method using octave band levels. A more refined procedure than SIL and PSIL developed for use in a very wide range of applications is Noise Criteria (NC or PNC). The most comprehensive and accurate procedure for predicting speech communication efficiency in noise environs is the Articulation Index. A final procedure, probably the most time-consuming and expensive, is to attempt to simulate the communication environment and directly measure the response of the system through intelligibility testing.

Sound level. The A-weighted sound level in decibels (dBA) is a single number representation of a noise measured with a sound level meter [8]. The A-weighting approximates sensitivity of the normal human ear to moderate level sound. Measured dBA values referenced in Figure 5 [135] provide relationships between communication capability and noise. This procedure is ideal for survey and monitoring purposes; however, it is unsuited for noise control and engineering purposes because detailed spectral information is lacking in the descriptor.

Speech interference level—speech interference level, preferred frequencies. SIL and NC procedures permit estimates of the acceptability of noises for communication based on octave band descriptions of the noise. Recent changes in noise

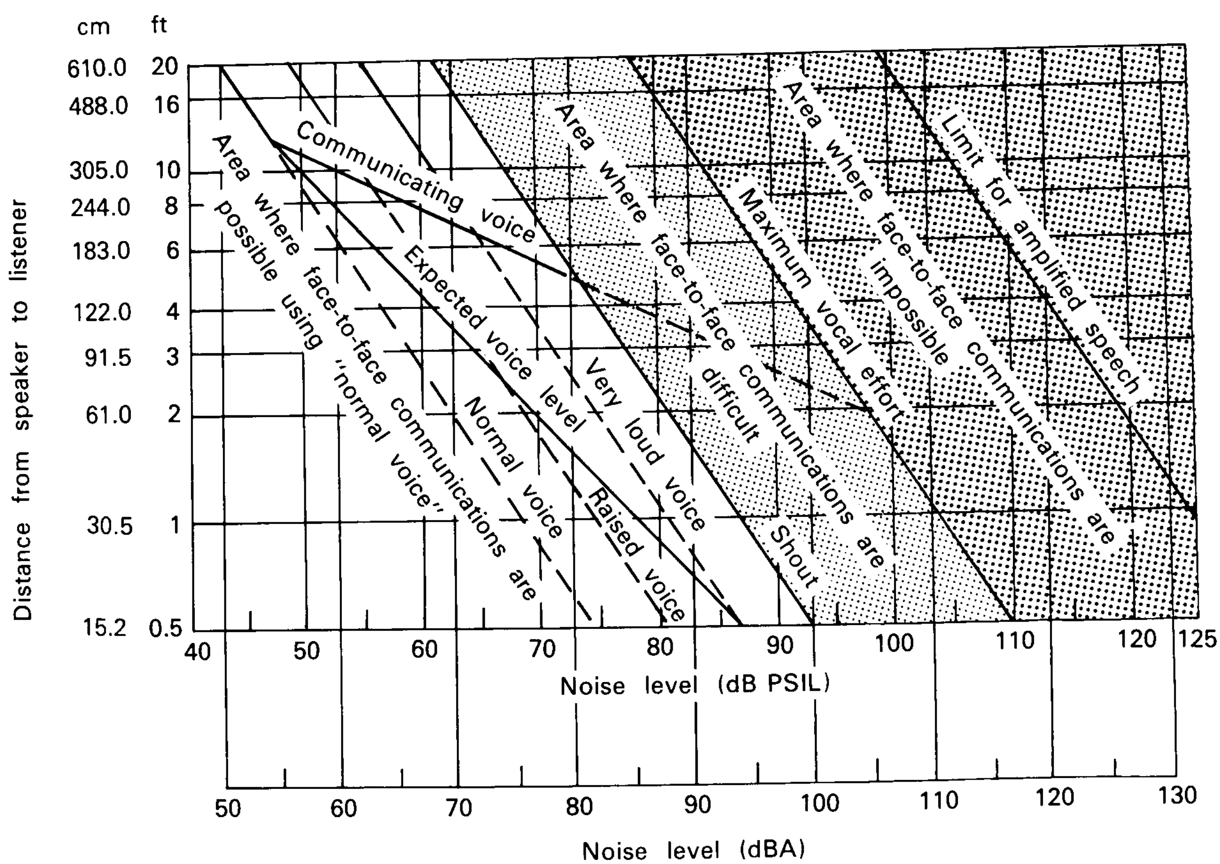


FIGURE 5.—Objective measures of noise level (PSIL and dBA) and corresponding communications capabilities [135].

measurement standards have resulted in two slightly different descriptions of the noise. New octave bands have been standardized for general use, and current noise measuring equipment is constructed to comply accordingly. The new octave bands, which have different center frequencies from the old octaves, are called *preferred* frequencies or octaves. The preferred center frequencies and the nonpreferred center frequencies of octave bands are presented in Table 2. To identify speech intelligibility prediction procedures that use the preferred center frequencies, the letter P is added to the nomenclature to produce PSIL and PNC.

SIL and PSIL [135] are single number criteria valid for noise exposures having a relatively uniform spectrum. The SIL is defined as the arithmetic average of the sound pressure levels (dB) of the noise in the three octave bands which contain most of the speech energy: 600–1200, 1200–2400, and 2400–4800 Hz. The PSIL, defined as the average octave band level of new or preferred octave bands centered at 500, 1000, and 2000 Hz, is called the three-band preferred octave speech interference level. PSIL and SIL levels for reliable communication at various distances and voice levels are shown in Figure 5. PSIL values are generally 3 dB higher than SIL values for the same noise exposure. It is acceptable practice to convert from one to the other by adding or subtracting 3 dB.

Noise criteria. Noise criteria (NC) are basically an expansion of SIL from a single number to sets of numbers representing octave band criteria. Noise criteria assume a reasonably steady and continuous spectrum. A new set of criteria curves has been formulated, which uses the new octave bands. These curves, called preferred noise criterion curves (PNC) [16], have levels in the bands below 125 Hz and above 1000 Hz that are lower than those of the original NC curves by 2–5 dB. Criteria curves and corresponding recommended indoor functional activity areas are described in Tables 3 and 4 for both NC and PNC.

To estimate communication performance for a given noise environment using either of these criteria:

1. determine the noise in octave bands
2. compare the octave band spectrum to the appropriate PNC criterion curve in Table 3
3. the criterion value just above the highest octave band level describes the noise environment
4. consult Table 4, which contains functional activities, to determine the level and quality of communication to be expected for that environment.

Articulation index. The most comprehensive procedure for predicting intelligibility in noise is the articulation index (AI) [7]. The AI is a calculation from physical and acoustical measurements made on a communication system which describes the intelligibility that might be expected for that system under actual test conditions. The speech spectrum and effective masking spectrum at the ear of the listener are required for the computation. The method is applicable for communication situations which involve male talkers.

TABLE 2.—*Preferred and Nonpreferred Center Frequencies of Octave Bands*

Preferred center frequencies	Band limits	Nonpreferred center frequencies	Band limits
31.5	22.4– 45	26.5	18.8– 37.5
63	45 – 90	53	37.5– 75
125	90 – 180	106	75 – 150
250	180 – 355	212	150 – 300
500	355 – 710	425	300 – 600
1000	710 – 1400	850	600 –1200
2000	1400 – 2800	1700	1200 –2400
4000	2800 – 5600	3400	2400 –4800
8000	5600 –11 200	6800	4800 –9600

TABLE 3.—*Octave-Band SPL Values Associated with Recommended 1971 Preferred Noise Criterion (PNC) Curves* [16]

Preferred noise criterion curves	31.5 Hz	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
PNC-15	58	43	35	28	21	15	10	8	8
PNC-20	59	46	39	32	26	20	15	13	13
PNC-25	60	49	43	37	31	25	20	18	18
PNC-30	61	52	46	41	35	30	25	23	23
PNC-35	62	55	50	45	40	35	30	28	28
PNC-40	64	59	54	50	45	40	35	33	33
PNC-45	67	63	58	54	50	45	41	38	38
PNC-50	70	66	62	58	54	50	46	43	43
PNC-55	73	70	66	62	59	55	51	48	48
PNC-60	76	73	69	66	63	59	56	53	53
PNC-65	79	76	73	70	67	64	61	58	58

Procedures for calculating AI may be based on the spectrum level of the noise and of speech present in 20 contiguous bands of frequencies, octave bands, or ⅓ octave bands of frequencies. The greatest precision is obtained with the 20-band procedure, the least with the octave band method. An appropriate worksheet must be used to calculate the AI. Sample worksheets are shown for the 20 contiguous bands (Fig. 6) and the octave bands of frequencies methods (Fig. 7). An example of the calculation of an AI by the octave band method is contained in Figure 8 for a relatively flat noise spectrum of moderate intensity. This calculation procedure may be followed in the example which provides an AI of 0.54:

1. Plot the octave band levels of the steady state noise reaching the listener's ears.
2. Adjust the idealized speech peaks curve to reflect the speech value in the system under test.
3. Determine the difference in decibels at the band center frequencies between the speech and the noise spectra. (Assign 0 to differences less than 1, and 30 to differences greater than 30.)
4. Multiply the difference values in each band by the weighting factor for that band, and add the resulting numbers to obtain the AI.

A number of factors which influence speech intelligibility scores, either individually or in combinations, may be quantitatively evaluated using the AI principle. Some of the factors are: (a) masking by steady state noise, (b) masking by nonsteady state noise, including the interruption rate, (c) frequency distortion of the speech signal, (d) amplitude distortion of the speech signal, (e) reverberation time, (f) vocal effort, and (g) visual cues. Of the many factors not evaluated by AI, there are: (a) sex of the talker, (b) multiple transmission paths, (c) combinations of distortions, (d) monaural vs binaural presentation, and (e) asymmetrical clipping, frequency shifting, and fading.

The relationship of AI to various measures of speech intelligibility is shown in Figure 9. The intelligibility score is dependent on the constraints placed on the message, i.e., the greater the constraint, the higher the intelligibility. No single value AI can be established as an acceptable communications criterion because of variations in proficiency of talkers and listeners, and in the nature of messages to be transmitted. AI is a consistent, reliable procedure for predicting relative performance of communications systems operating under given conditions. Present-day communication systems usually have design goals of AIs in excess of 0.5. An AI of 0.7 appears appropriate as a goal for systems which will operate under a variety of stress conditions and with many different talkers and listeners of varying degrees of skill.

Measurement of intelligibility. In some situations the speech and/or noise characteristics may not satisfy the basic assumptions underlying the standard calculation procedures. Unusual noise environs, whole-body vibration in noise, and artificial atmospheres and noise are examples. The communication efficiency with talkers and/or listeners in the environment of interest must then be measured. Some intelligibility assessment procedures are widely accepted through standardization and through usage. One sensitive test of speech intelligibility is the Phonetically Balanced (PB) Monosyllabic Word Intelligibility Test [6]. This procedure consists of trained talkers reading lists of phonetically balanced material to trained listeners under communication system features being evaluated. A score of about 70% on the PB word lists corresponds to more than 90% intelligibility for sentences.

Speech communication, using good sound protector-communications units (i.e. earphones under ear protectors and a shielded microphone reducing speech masking by the ambient noise) is adequate in most operational aerospace ground-maintenance situations. The performance of these units has not been determined in the noise fields of present and future rocket systems, of large jet engines of the C–5A or SST, and with VTOL and VSTOL type aircraft.

Artificial atmosphere. Speech communication has been evaluated in special or unusual environments of interest to aerospace operations. Helium, once considered a possible component of the life-sustaining atmosphere of some space vehicles and orbital stations, was investigated [70, 106]. This research described speech responses in helium concentrations ranging from 0–80% at pressures of 760–258 mm Hg. Effects of helium were found positively related to the amount of helium present, i.e., the greater the amount of helium, the greater the effect on speech. In general, helium speech showed: (1) good intelligibility, (2) less vocal output than air, (3) shifts of speech energy (vowels) to higher frequencies, (4) greater susceptibility to masking by ambient noise than speech in air, and (5) a strange, unnatural quality. These characteristics are imposed by elements of the physical environment, thus cannot be significantly improved by crewmember training and experience.

Vibration. Various powered phases of space missions as well as high-speed, low-altitude flight are characterized by severe vibration, buffeting, and intense noise. The speech of individuals subjected to these stimuli is altered to a tremolo-like voice quality corresponding in some degree to the frequency of the vibration [103]. Word intelligibility is reduced, particularly by vibrations at 6 to 7 Hz. The vibrated speech is masked by noise to a greater extent than might be expected. Speech continues to deteriorate with increasing levels of acceleration.

Performance

Adverse effects of noise on sensorimotor performance and cognitive function have not been

TABLE 4.—*Recommended Noise Criteria Ranges for Steady Background Noise as Heard in Various Indoor Functional Areas* [16]

Type of space (and acoustical requirements)	PNC curve	Approximate sound level (dBA)
For sleeping, resting, relaxing; bedrooms, sleeping quarters, hospitals, residences, apartments	25 to 40	34 to 47
For fair listening conditions; laboratory work spaces, drafting and engineering rooms, general secretarial areas	40 to 50	47 to 56
For moderately fair listening conditions; light maintenance shops, office and computer equipment rooms	45 to 55	52 to 61
For just acceptable speech and telephone communication; shops, garages, power-plant control rooms, etc. Levels above PNC–60 are not recommended for any office or communication situation	50 to 60	56 to 66
For work spaces where speech or telephone communication is not required, but where there must be no risk of hearing damage	60 to 75	66 to 80

consistently demonstrated. Performance efficiency has been variously reported to increase, deteriorate, or remain unaffected by noise. In general, efficiency may improve when noise exposure functions to isolate performance from acoustic distractions. The efficiency may deteriorate when the noise itself is a distracting influence on tasks which require attention and concentration over long work periods. Although numerous, experimental investigations on effects of noise on performance have failed to provide an integrated framework for the establishment of exposure criteria. Questions remain unanswered concerning the amount of performance impairment to be expected for specified sets of noise exposure conditions.

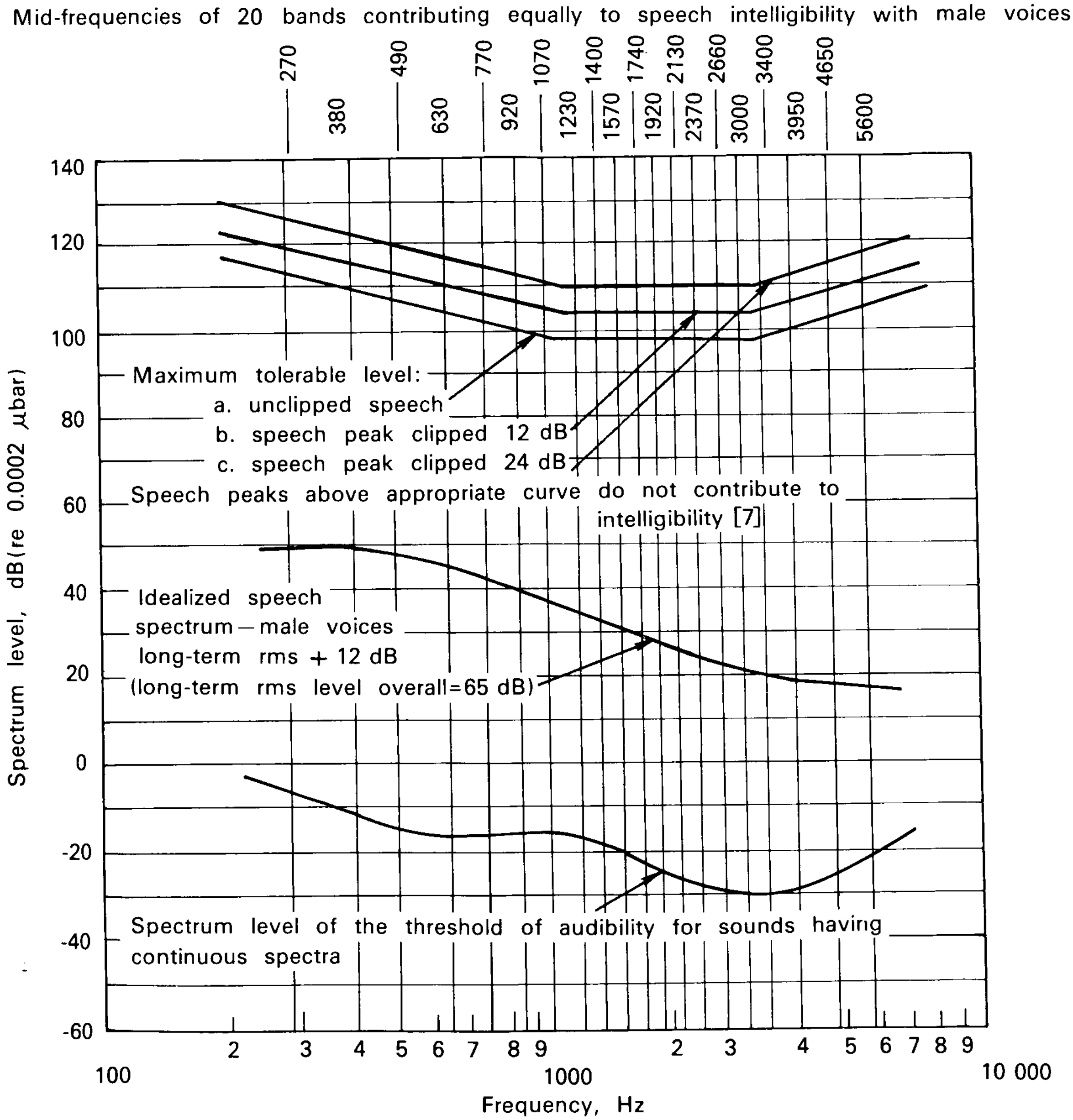


FIGURE 6.—Work sheet for articulation index, 20 contiguous bands method [7].

Kryter [72] presents a comprehensive discussion of a great deal of key work accomplished over the past 10 years. He reviews the results as well as various theories to explain motor performance in noise. In summarizing, he suggests that noise will not "directly interfere with mental or motor performance." He asserts noise effects on mental and motor nonauditory tasks to be negligible below about 27 dBA, possibly beneficial between about 27 and 67 dBA due to arousal and isolation from distraction, and possibly detrimental above about 67 dBA due to overarousal, aversion, and distraction from the task.

Noise Combined with Vibration

Simultaneous exposure to noise and vibration is exceedingly common in current transportation systems and in powered flight phases of space activities. The effects of these combined stimuli on performance cannot be predicted from knowl-

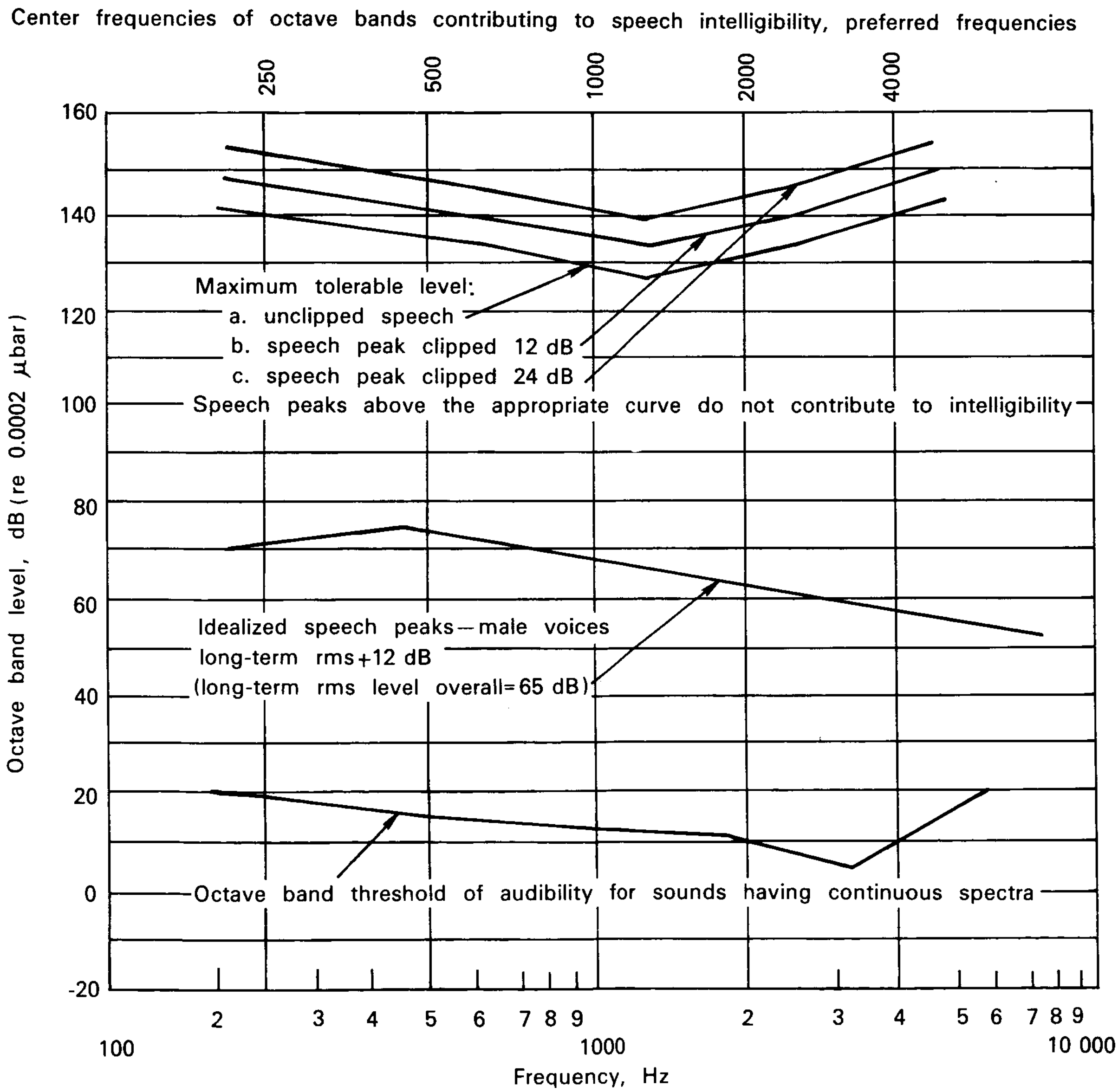
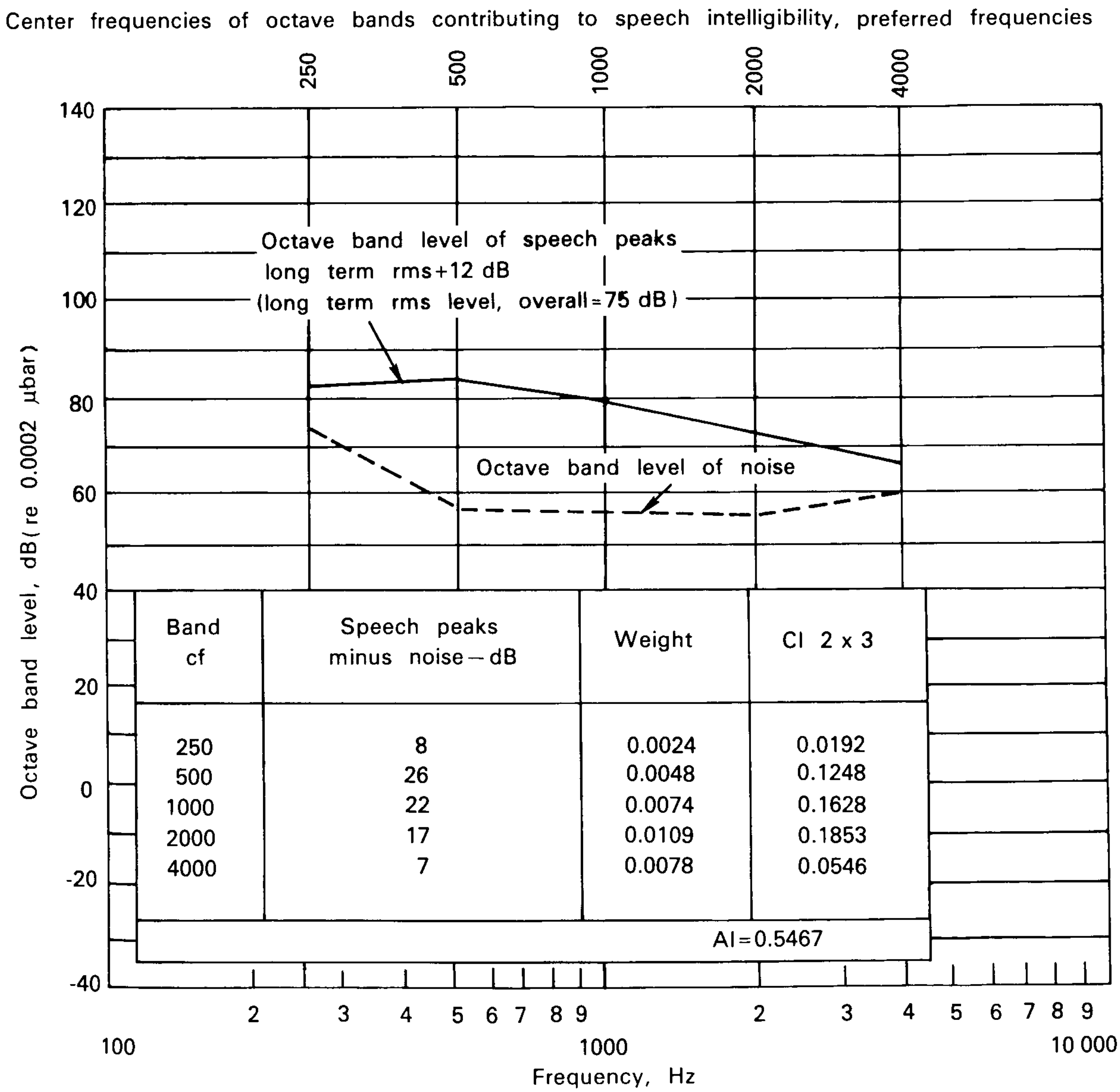


FIGURE 7.—Work sheet for articulation index, octave band method, preferred frequencies [7].

edge of single-stress effects. Since consistent information is lacking about effects on performance from noise and vibration individually, it is not surprising that even less information exists relative to their combined effects. Scientific interest in the experimental investigation of this combined stimulus is relatively recent. In a few studies, motor performance has been examined on a two-dimensional complex tracking and reaction time task, and cognitive performance on a short-term memory/subtraction task. Results from motor performance studies were not conclusive. However, there was some consistency between studies for the cognitive task [125]. An additional study of the effects of the combined noise and vibration on the mental arithmetic task as a function of time of day revealed no significant differences in performance measured at 6 a.m. and at 3 p.m. Ioseliani [63] reports decreased intellectual performance in noise combined with



Band cf	Speech peaks minus noise – dB	Weight	CI 2 x 3
250	8	0.0024	0.0192
500	26	0.0048	0.1248
1000	22	0.0074	0.1628
2000	17	0.0109	0.1853
4000	7	0.0078	0.0546
			AI = 0.5467

FIGURE 8.—Example of articulation index calculation using the octave band method [7].

vibration: 70% of the degradation was due to vibration, and 30% due to the noise component.

The environmental stress of heat was added to that of noise and vibration by Grether et al [44, 45] in two studies which examined effects on performance and were specifically oriented to the combined stress of space activities. The subjects were exposed to heat 49° C (120° F), noise (105 dB), and z-axis vibration (5 Hz, 0.30 g peak) singly and in various combinations. Results suggest that the combined stress condition produced less of an effect on performance than the individual stressors. The greatest impairment of performance resulted from the vibration stimulus alone. These results should not be interpreted as conclusive because of the limited number of investigations and meager amount of information.

Stresses are typically encountered simultaneously in real life situations, instead of individually, as they are ordinarily investigated.

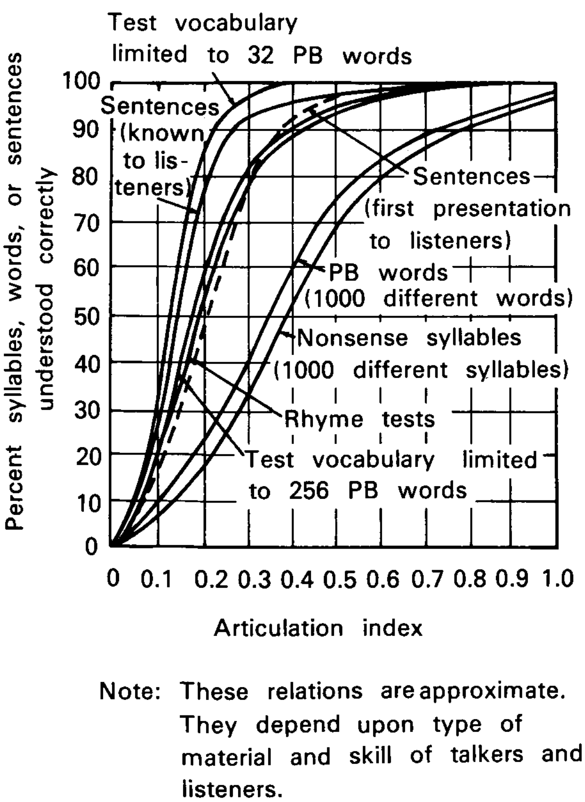


FIGURE 9.—Relation between AI and various measures of speech intelligibility [7].

Investigators working in the area of combined stresses point out the complexity of these multistress situations which are further confused by interactions relating to task, instructional, and situational variables. The problems encountered in single-stress research and the little experience accumulated when stresses are combined suggests that the prediction of human performance capability in combined-stress situations is likely to be very difficult for some time in the future. There are, however, no documented situations in which acoustical energy has directly acted upon individuals so as to seriously interfere with task performance in environments typical of those experienced by aerospace crews.

Complex Reactions

Numerous psychologic factors in the lives of individuals contribute to the manner in which they respond and will respond to noise and sonic booms from aerospace activities of the present and future. The interaction of these psychologic factors with noise exposure results in the wide range of behavior in response to noise, and is described as complex reactions. Some general models have been proposed for various actions of the intruding noises and corresponding responses of those exposed to it.

Noise. Acoustic energy is undesirable when attention is called to it unnecessarily or it interferes with routine activities in the home, office, shop, recreational area, or elsewhere. Numerous techniques based on physical stimuli are available and in use to assess noise exposure effects on people in work and living spaces and to estimate individual and community reaction to them. In the past, most approaches to this question have been based upon loudness functions and methods for calculating loudness of sounds. A current concept, which has gained widespread acceptance and usage, maintains that individual and community reaction to a sound is determined by the annoyance or unwantedness of the sound instead of its loudness. The subjectively judged unwantedness of a sound is described as its perceived noisiness (PN). The perceived noisiness concept supposes that unacceptability of a sound may be adequately determined from physical measures of sound. The unit of noisiness obtained from calculations—using the physical or objective measurements of the sound—is defined as the perceived noisiness in decibels or PNdB.

Relationships between various PNdB levels and the nature of community reactions that correspond to them have been defined on the basis of data from airport noise experiences as well as both laboratory and field research. These relationships are compiled for use in estimating reactions and a step-by-step procedure is available for arriving at PNdB values from the physical measurements of the noise. A comprehensive discussion of the basic concept of perceived noisiness, including various modifications and refinements intended to extend the usefulness of the procedure, is presented in detailed form in Kryter's discussion [72].

Most schemes currently in use throughout the world for estimating total exposures are based upon some form of loudness function or of the perceived noisiness concept. Each nation also modifies whatever basic concept is used relative to its own needs, criteria for percent of population affected, basic research data of most interest to them, and the like. The wide variety of techniques for describing the acoustic stimulus can be reduced to a common denominator for convenient comparison [33]. Approximate equivalences between noise exposure indices from a number of different nations are shown in Figure 10. Each of these procedures is used to estimate responses of communities and to determine compatible land usage for corresponding noise exposures.

Present indices for predicting complex reactions to total noise exposure may not be directly appropriate to aerospace activities. Total noise exposure implies numerous individual exposures daily over a minimum of many days. Aerospace activities, other than those such as static rocket firings, will likely occur one or two times per week as a maximum, at least for the foreseeable future. Appropriate corrections might be applied to the basic procedures to permit their use with noise exposures of the aerospace systems.

Sonic boom. National and international attention is directed at human response to sonic boom from the standpoint of commercial supersonic transport aircraft, as well as current and future aerospace activities which will involve frequent exit from, and reentry into, the Earth's atmosphere at supersonic speeds. Investigative efforts continue in a number of areas to determine valid tolerance criteria. Recent research activities in both laboratories and communities have provided a framework of information within which this stimulus may be better understood [40]. Estimates and observations of sonic boom exposures are summarized in Table 5.

Direct physiological injury of humans due to exposure to the level of sonic booms typically experienced in communities and to special experimental studies has not been documented. The auditory mechanism is exceedingly sensitive to variations in pressure; however, no adverse effects of sonic booms on hearing acuity have been measured. Startle and interference with routine living and work activities may lead to complex reactions of annoyance, which are problems of considerable proportion. The extent to which individuals adapt to startle after repeated exposures over days and weeks is unknown.

High-Intensity Noise Effects

Some noise environs during launch and static firings of aerospace vehicles are short-duration exposures at overall sound pressure levels ranging from 120 to 170 dB and greater. When individuals are without adequate hearing protection against these noises, likely they will have pain and severe acoustic trauma during relatively brief exposures. Whole-body or nonauditory effects may be experienced at these intensity levels in spite of using good hearing protection.

Steady state. Steady-state acoustic energy at these levels, and particularly for lower frequencies, is clearly felt as well as heard. The threshold of feeling for the airborne sound is about 10 dB below the threshold of aural pain for energy in the midfrequency range. The acoustic energy activates mechanoreceptors throughout the body [71, 141]. The stimulus is perceived by cutaneous receptors, viscera, and the vestibular system. Sinuses, mucous membranes, and proprioceptors also respond. Overall sensations are strange and somewhat disturbing even to individuals accustomed to noise exposure. Vertigo, nausea, vomiting, and occasional disorientation are reported

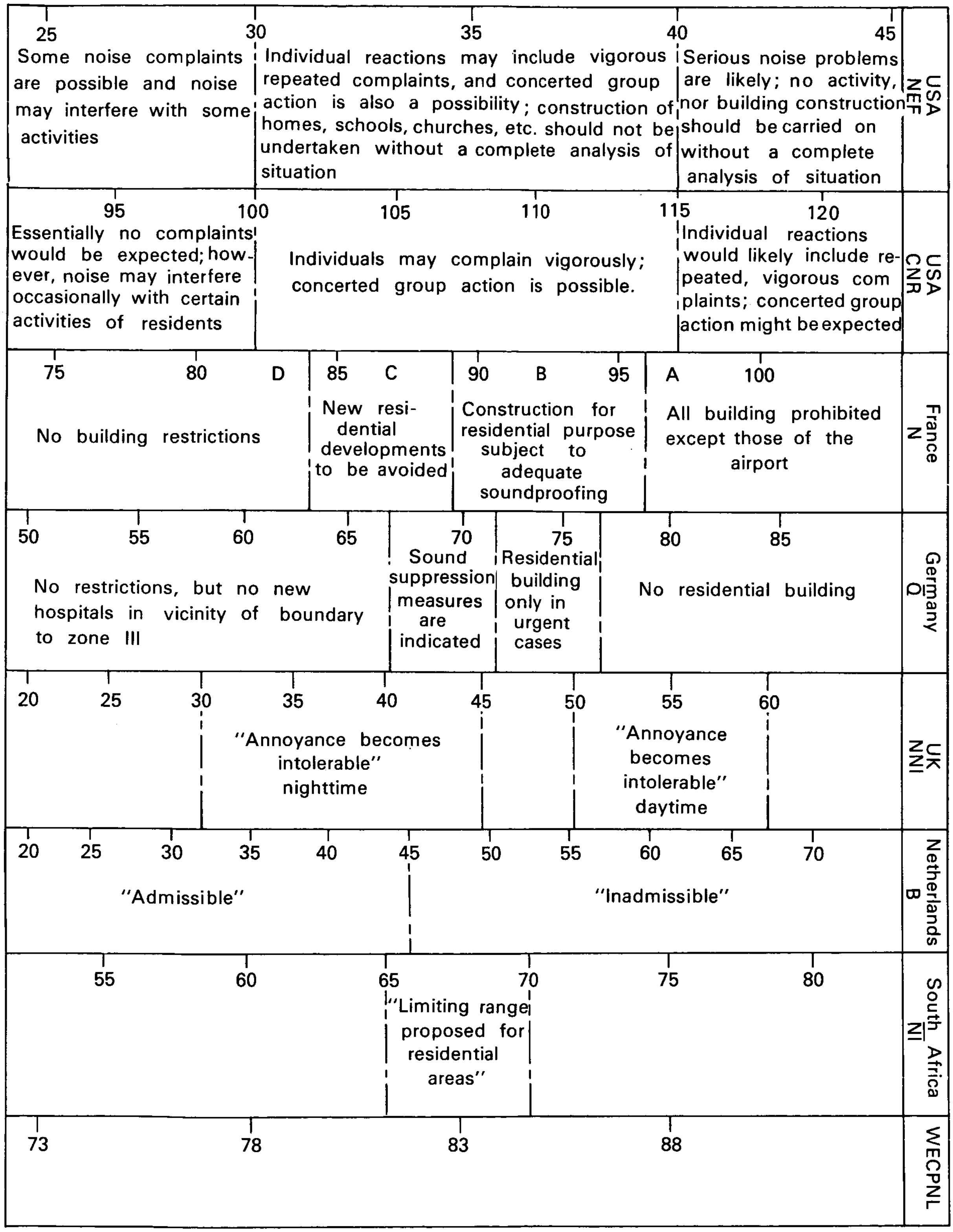


FIGURE 10.—Approximate relationships between noise exposure indices [33].

TABLE 5.—*Estimates and Observations of Sonic Boom Exposure*

Peak overpressure		Predicted and/or measured effects	
lb/ft²	dyn/cm²		
0–1	0–478	Sonic booms from normal operational altitudes: typical community exposures (seldom above 2 lb/ft^2, or 957 dyn/cm^2)	No damage to ground structures; no significant public reaction day or night
1.0–1.5	478–717		Very rare minor damage to ground structures; probable public reaction
1.5–2.0	717–957		Rare minor damage to ground structures; significant public reaction, particularly at night
2.0–5.0	957–2393		Incipient damage to structures
20–144	957×10^3–6.8×10^4	Measured sonic booms from aircraft flying at supersonic speeds at minimum altitude; experienced by humans without injury	
720	3.44×10^5	Estimated threshold for eardrum rupture (maximum overpressure)	
2160	1.033×10^6	Estimated threshold for lung damage (maximum overpressure)	

or observed during, and sometimes after, the acoustic exposure is terminated. Continuous exposures produce irritability and fatigue, which may persist for many hours after exposure.

Personnel should not be permitted in noise fields of 150 dB, as a rule, regardless of the hearing protection worn, because of possible adverse nonauditory effects. In environs near these levels, individuals who are susceptible to nonauditory or auditory effects should be monitored closely.

Impulse. Impulse noises, with signal durations of less than 1000 ms, commonly occur at peak positive pressure values ranging from 120 to 170 dB and greater for weapons fire, explosions, impact devices, and near field sonic booms. The relatively little energy in the very brief and rapidly rising and falling single impulse is significantly less effective in adversely affecting man than is steady-state noise. When high-level impulses occur repeatedly, however, their potential effect on the auditory system increases. Aerospace impulsive noises are likely to be single impulses and may be limited to low-level sonic booms for present generation systems.

Infrasound. Aerospace propulsion systems are a major source of intense infrasound during launch. Noise spectra containing intense low-frequency and infrasonic energy may excite body parts such as the chest, abdomen, eyes, and sinus cavities, and cause concern, annoyance, and fatigue. Psychologic responses accompanying these physiologic effects may result in even more complex reactions to such exposures.

In one comprehensive study, an attempt was made to systematically assess effects on various human responses of a number of existing high-intensity infrasound and low-frequency energy sources [97]. Representative spectra and levels of acoustic energy to which noise-experienced subjects were exposed in a series of separate tests are shown in Figure 11. Subjects wore hearing protective devices in those exposures containing high-level audiofrequency energy, but participated open ear or experimented with various types of protectors when the high-frequency energy was relatively low.

Subjective human tolerance data relating to the various noise exposures are also summarized in Figure 11. Voluntary tolerance limits were approached for frequencies below 100 Hz at levels of 150–154 dB as evidenced by symptoms of nausea, giddiness, coughing, choking, and the like. This confirms the maximum permissible exposure limit of around 150 dB for infrasound. The levels and behavior described are approaching maximum subjective tolerance for the durations experienced, although subjects reported that tolerance limits had not been reached. Lower levels of exposure are presumed to be safe and/or acceptable for longer periods.

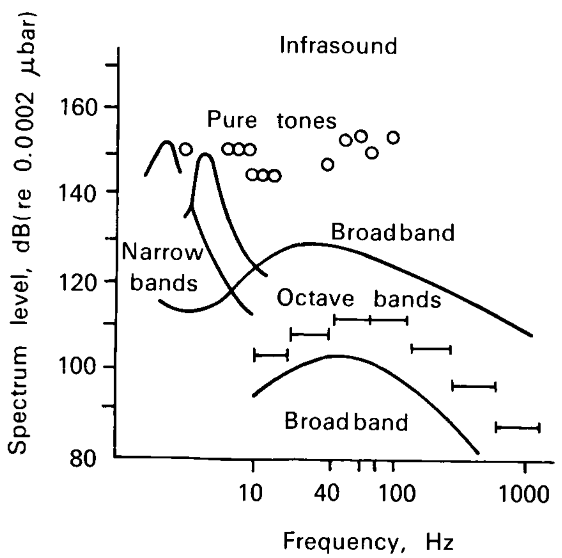
Ultrasound. Numerous ultrasound noise sources are present in aerospace activities and equipment such as rocket and jet noise, cleaning and measuring devices, drilling and welding processes, and power and communication control. Documented evidence of detrimental effects on personnel exposed to airborne ultrasound is scarce, in part because ultrasound is particularly amenable to atmospheric absorption and to noise control measures. The use of standard hearing protective devices essentially eliminates complaints of undesirable exposures.

Subjective symptoms of ultrasonic exposure were attributed earlier to apprehension of the exposed individual; however, recent evidence correlates symptoms with specific exposure conditions [2]. Energy at frequencies above about 17 000 Hz and in excess of 70 dB produces subjective effects. Individuals who cannot hear in this region do not experience the subjective symptoms. Women appeared to experience symptoms more often than men, and younger men more often than older men. This would appear to be consistent with the relative hearing abilities of the three groups and the described relationship with the energy above 17 000 Hz and 70 dB.

Many ultrasound exposures also contain substantial energy in the audiofrequency range and this lower frequency energy is commonly responsible for the complaints. In these instances, reducing the level of the audio portion of the exposure results in disappearance of subjective symptoms. Nevertheless, when airborne ultrasound at the position of the operator's head exceeds acceptable levels, subjective responses of ill effects may be expected from exposed personnel.

Noise Effects in Space Operations

The aerospace noises (described in the first section of this chapter) vary as a function



Tolerance data

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

Representative low-frequency and infrasonic test environments

FIGURE 11.—Infrasound exposures and corresponding subjective responses.

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of the phases of the spaceflight profile and in their potential effects on the space vehicle crewmembers, ground-support crews, and residents in communities where the acoustic energy may intrude. A summary of space operations noise exposure and potential environmental impact is contained in Table 6.

Launch. At ignition, rocket exhaust noise suddenly attains very intense sound pressure levels which radiate very great distances from the launch site.

Flight crew. Noise reaches the crew compartment through structure-borne and airborne transmission. However, transmission loss in space systems such as Apollo is sufficient to reduce outside levels in excess of 150 dB to crew station levels of 120–125 dB. Additional protection from the acoustic energy is provided by crewmembers' space suit-helmet configurations. Sound levels at the ears of crewmembers range from a maximum of near 120 dB for the very low frequencies to 90 dB and less at the higher frequencies above 2000 Hz. As the vehicle lifts off, the level of propulsion noise decreases and that of aerodynamic noise increases. Approximately 60 s after launch, maximum levels of around 120 dB are again encountered at the crew stations. From 60 to 110 s, the noise gradually decreases to relatively low levels below 100 dB which are dominated by on-board systems.

Noise exposures experienced by crewmembers during launch are not of sufficient magnitude in the short exposure periods to create adverse biomedical or performance effects. The total very brief duration and maximum levels are attained only momentarily before they gradually decrease. Voice communication is the most vulnerable potentially threatened function under these conditions. Its efficiency is limited by the basic instrumentation system as well as the acoustic isolation and protection of the headset and special features of the microphone designed to effectively operate in noise environs. Voice communication system technology and the experience of several space launches in the USSR and US indicate that voice communication is adequate for current rocket-system launch noises.

Shirt-sleeve crew environments provide less whole-body protection against noise exposure than pressurized space suits. Whole-body exposure levels of about 125 dB may be sufficient to stimulate mechanoreceptors in some individuals. However, the training and experience of crewmembers, in addition to the very brief durations of the exposures, again suggest that no significant adverse effects will occur.

In general, space suit and shirt-sleeve crew environments contain intense acoustic energy during launch; however, the brief duration of the intense exposures and special provisions for the situation preclude adverse physiologic or psychologic effects.

Ground crew. The rocket noise at ignition is the most intense exposure experienced by ground crew personnel. Overall levels at the exhaust of vehicles such as Saturn V reach 175 dB decreasing to levels of 150–155 dB in the near field around vehicles as close as 182.9 m (600 ft) from the pad. The overall level decreases as the vehicle accelerates away from the launch site. Levels are of sufficient intensity to produce both physiologic and psychologic effects; however, such undesirable effects may be avoided easily with adequate protection of the ground crews. Concrete bunkers and other structures, as well as personal hearing protection, will provide sufficient protection to insure no adverse effects on crewmembers and their tasks. Ground crew voice communication may be assured with the use of appropriate hearing protector-voice communication systems.

Communities. The low frequency and infrasonic components of the launch noise propagate freely over great distances with relatively little attenuation. Sound pressure levels of 105 dB for energy below 20 Hz have been measured 16.09 km (10 mi) from a rocket site during launch. Communities as far away as 32.2 km (20 mi) clearly experience this low-frequency energy. It is possible that band pressure levels above 100 dB may excite vibration in structures and furnishings where people reside and work, causing disturbances and annoyance. Unless structures are so close to the launch site that minor property damage is precipitated, community acceptance may be relatively high for the infrequent exposures of present space operations.

Cruise. The controlling noise exposures in crew compartments are produced by on-board support equipment. Data from measurements taken in various crew areas in the Apollo command module indicate relatively moderate overall levels of 65–70 dB. These levels have proven acceptable, although not necessarily ideal, for space ventures of several weeks. No undesirable aftereffects have been reported due to noise.

Effects of exposure to relatively low level (60–70 dB) on-board noise for long-duration missions have not been fully described. In nonspace

TABLE 6.—*Summary of Space Operations, Noise Exposure, and Potential Environmental Impact*

Operation	Exposure	Spacecrew	Groundcrews	Community
Industrial support of space systems	Noise		Industrial noise exposure; 8-h d; compliance with DoL 90 dBA criteria	Potential problems where noises intrude into neighboring communities
Launch	Noise	Brief exposures of 125–130 dB SPL in crew area; less than 120 dB at ear; hearing protection and voice communication adequate with current systems; no adverse effects due to protection and brief exposures	Very intense levels as high as 150 dB SPL at 600 ft from pad; adverse effects without protection provided by structures and/or hearing protectors	Intense levels perceived at great distances; low frequencies of 115 dB 3 miles from pad; 105 dB at 10 miles; infrequent occurrence, brief duration contribute to acceptability
	Sonic boom	Not perceptible		
Cruise	Noise	On-board systems; ambient levels of 60 70 dB; noise levels higher during certain operation, levels tolerable for brief missions of several days; acceptable levels for missions of 6–18 mo not determined	Not applicable	Not applicable
Reentry	Noise	Noise similar to maximum aerodynamic noise at launch; greater duration, may need to assume voice comm capability for space shuttle type reentry	Brief, low-level exposures at landing	Negligible; infrequent
	Sonic boom	Not perceptible	Not perceptible, boom occurs some distance from landing site	Space shuttle-type reentry may expose large areas of Earth's surface; impact depends on number of people exposed, etc.
Static firing	Noise	Not applicable	Very intense levels of 150 dB at 600 ft; must use protection; durations and frequency of occurrence much greater than launch	Noise propagates far distance into communities; duration of runs; frequency of occurrence, time of day, etc., will contribute to acceptability; this may be worse community exposure situation

activities, noise exposure is generally considered "off" during sleep periods at which times the affected biologic systems may recuperate. During cruise phases of space flight, noise exposure is continual, recuperation periods are not available, and potential effects during many months are uncertain. The maximum permissible level originally proposed by Yuganov et al [141], of about 65 dB, is considered acceptable for 30–60 d missions; however, it may be too high for continuous exposures 24 h/d over many months and even years. He does indicate that 50–60 dB is desirable in general and required for sleep and rest, and that 85 dB or less is maximum for a 4-h watch.

Some on-board systems which may produce high noise levels are used only periodically and may not be reflected in the measured figures of 60–70 dB overall noise level. Systems which produce higher level noises for periods less than 24 h should be designed so that noise exposures comply with appropriate hearing damage risk and voice communication criteria (24-h criteria are preferable, otherwise use 8-h criteria).

Reentry. The impact of noise exposure during reentry is dependent upon the specific reentry vehicle and mode of operation. Current systems which utilize the atmosphere to retard the vehicle's speed upon reentry and a parachute delivery of the capsule to the Earth's surface involve noise exposures to only the crewmembers. Aerodynamic noise of approximately the same maximum levels experienced during launch will also occur during reentry. The duration of reentry exposure is longer than at launch. However, overall impact of the exposure appears to be no greater than during launch and is acceptable.

Future space systems are expected to reenter the atmosphere in an operational mode similar to that used in pilot-controlled high-performance aircraft. The maximum aerodynamic noise levels should not differ markedly from those of other systems on reentry; however, the exposure duration will likely be prolonged due to the relatively flat trajectory of the vehicle. Adverse effects of noise exposure on crewmembers are not expected.

Sonic booms are generated by the supersonic speeds of vehicles on reentry to the atmosphere from space. Parachute-delivered systems' landing areas are generally located in remote regions over land or water. Thus, the impact of the sonic boom on structures and people may not be a matter of major concern. Pilot-controlled systems will gradually decelerate and land at a few designated spaceport facilities, generally close to populated areas. Sonic booms are expected over large areas of the Earth's surface during these operations, the magnitudes of which are estimated to be small. Their impact on communities is not yet determined. Similar to sonic boom exposures in general, the acceptability is related to such factors as frequency, whether or not minor property damage accompanies the booms, and, of course, magnitude of the booms.

Sonic booms at launch will reach the ground only for certain flight trajectories. Launch corridors, selected for safety and other reasons, usually restrict the use of these areas by non-space-related personnel and activities. It is expected that the effects of sonic boom on structures and persons exposed during launch will follow the same rules for acceptability.

Static firing. Propulsion systems generate broadband noise which radiates from the test site during captive firing. Although the directivity may be significantly affected by exhaust deflectors, the nature of the physical stimulus is similar to that at ignition. Maximum energy is in the low and infrasonic frequencies, but intense ground-borne noise is also present with the airborne noise during static testing. The frequency of the firings and duration of individual exposures during rocket engine test are considerably lengthened. If the test site is not sufficiently distant from residential communities, the possibility of vibrating buildings and creating noise annoyance may be significantly increased. Similar to launch noise, intensity levels close to the pad are hazardous for unprotected personnel.

Control Measures

Quantitative engineering analysis and prediction techniques are available for treating elements of the acoustic-exposure problem ranging from the noise source to the human receiver.

Control of noise at its source is most desirable from both engineering and human exposure standpoints. Since this form of control is not practical in many situations, other measures must be implemented in dealing with particular noise environments.

Source. The engineering capability to reduce noise exposure should be exploited as the initial step in control programs or efforts. Many sources, however, are not amenable to such treatment. Even after engineering treatments, levels are not reduced below limiting exposure values. Additional measures to control the noise at its source must be considered.

Noise exposure may be reduced, in many situations, by modification of the operational activity producing, or associated with, the noise. Shorter running periods, operations at slower speeds, appropriate rest intervals, and the like, may reduce power, noise level and duration, and total exposure. The overall health, safety, and well-being of personnel affected is the primary concern in a modification of activities to reduce noise exposure. Generally, this approach can be implemented without any compromise of the operational activity.

A practical and highly effective noise control measure is simply to increase the distance between a noise source and receivers. Major noise sources such as rocket and engine test, and maintenance facilities may be located far distant from occupied areas. The majority of such operations usually achieve noise reduction through remote siting of projects. The amount of attenuation to be expected with increased distance may be grossly estimated using the inverse square law which dictates a 6 dB change in sound pressure level for each halving or doubling of the distance from source to receiver. Small items of noisy equipment should also be physically located at the greatest practical distance from the receivers to take advantage of the distance attenuation provided by nature.

Receiver. Noise control is accomplished at locations occupied by personnel with sound treatment of the facility or vehicle and by providing personal protection against the noise. Sound treatment may involve increasing the transmission loss characteristics of structures against external noise, increasing the absorptive properties of work and living spaces against the noise, directly treating the internal source, or all of these.

Sound treatment in aerospace vehicles usually includes action against both internal (air conditioner, pneumatic pumps) and external (aerodynamic, engine) noise. Noise exposures may be below levels which threaten hearing yet be of sufficient magnitude to interfere with speech communication or cause general discomfort and annoyance. More effective sound treatment is then required. Sound treatment involving additional acoustic material to the vehicle is accomplished at a weight cost. Consequently, the amount of noise reduction realized in aerospace vehicles may be determined by compromise between weight cost and allowable exposures for crewmembers or speech communication capabilities. This compromise may be significantly influenced by the availability and use of personal ear-protective devices. Sound treatment of ground facilities is not ordinarily hampered by weight penalties, making noise reduction relatively easier to accomplish in this respect than in airborne systems.

Protection of the Organism

When excessive noise exposures cannot be reduced by generation and propagation noise control measures, general protection of the organism must be considered. Personal hearing protective devices are those inserted into the external ear canal or those that cover the external ear to reduce the amount of acoustic energy at the eardrum. The expected range of hearing protection (in dB) provided by good protective devices is summarized in Figure 12. Hearing protectors permit individuals to undergo more intense and longer duration exposures than with the unprotected ear and still remain within established health standards. Exposure criteria are essentially extended by proper use of hearing protection. The amount of protection obtained with these devices is limited by tissue and bone conduction of the head. Sound bypasses the protector and reaches the inner ear through tissue and bone pathways of the head [39].

Intense noise exposure may induce a variety of nonauditory effects including those on the abdomen, chest, internal organs, respiration, and vibrotactile sensitivity [71, 97]. Total head enclosures, which include antinoise helmets, will increase tolerance to noise influences primarily mediated via the auditory system and tissue and bone conduction pathways of the head. Maximum general protection of the organism against the most intense noises may require antinoise suits or total body enclosures. An antinoise suit (such as that shown in Figure 13) worn with conventional hearing protectors provides additional protection and comfort against the whole-body effects of intense noise. Antigravity flying suits and space suits provide some additional protection and comfort for the organism against noise.

Hearing protection	Frequency, Hz				
	1-20	20-100	100-800	800-8000	> 8000
Earplugs	5-10	5-20	20-35	30-40	30-40
Earmuffs	0-2	2-15	15-35	30-45	35-45
Earplugs and earmuffs	10-15	15-25	25-45	30-60	40-60
Communication headsets	0-2	2-10	10-30	25-40	30-40
Helmets	0-2	2-7	7-20	20-50	30-50
Space helmet (total head enclosure)	3-8	5-10	10-25	30-60	30-60

Entries show approximate minimum and approximate maximum protection available from various devices

FIGURE 12.—Expected range of hearing protection for good protective devices.

Limiting Noise Levels

Aerospace noise sources generate acoustic energy over a wide spectrum ranging from below 1 Hz to well above 100 000 Hz. The differential effects on man produced by various segments of acoustic-exposure frequencies necessitate the definition of limiting noise levels for a number of portions of the spectrum. Generally, exposure limits may be defined specifically for infrasound

FIGURE 13.—Antinoise suit designed to provide general protection of the organism in intense noise.

(1–20 Hz), audiofrequencies (20–20 000 Hz), ultrasound (20 000–100 000 Hz) and impulsive sound. Some of the exposure limits considered are well-substantiated by experimental evidence and experience; others must be considered tentative until more evidence is forthcoming. Exposure criteria or guidelines are summarized for various categories of acoustic energy in Figure 14.

Infrasound

Range 1–20 Hz. Limiting noise levels considered acceptable are 150 dB at 1–7 Hz, 145 dB at 8–11 Hz, and 140 dB at 12–20 Hz. These values apply to discrete frequencies or octave bands centered at the stated frequencies. Maximum exposure duration is 8 min with 16 h rest between exposures. Satisfactory insert earplugs will increase permissible levels by 5 dB for the same exposure times; earplugs are strongly recommended for all intense infrasound exposures to minimize subjective sensations. Levels above 150 dB should be avoided even with maximum hearing protection because general nonauditory responses occur.

Range 20–100 Hz. The tentative limiting levels

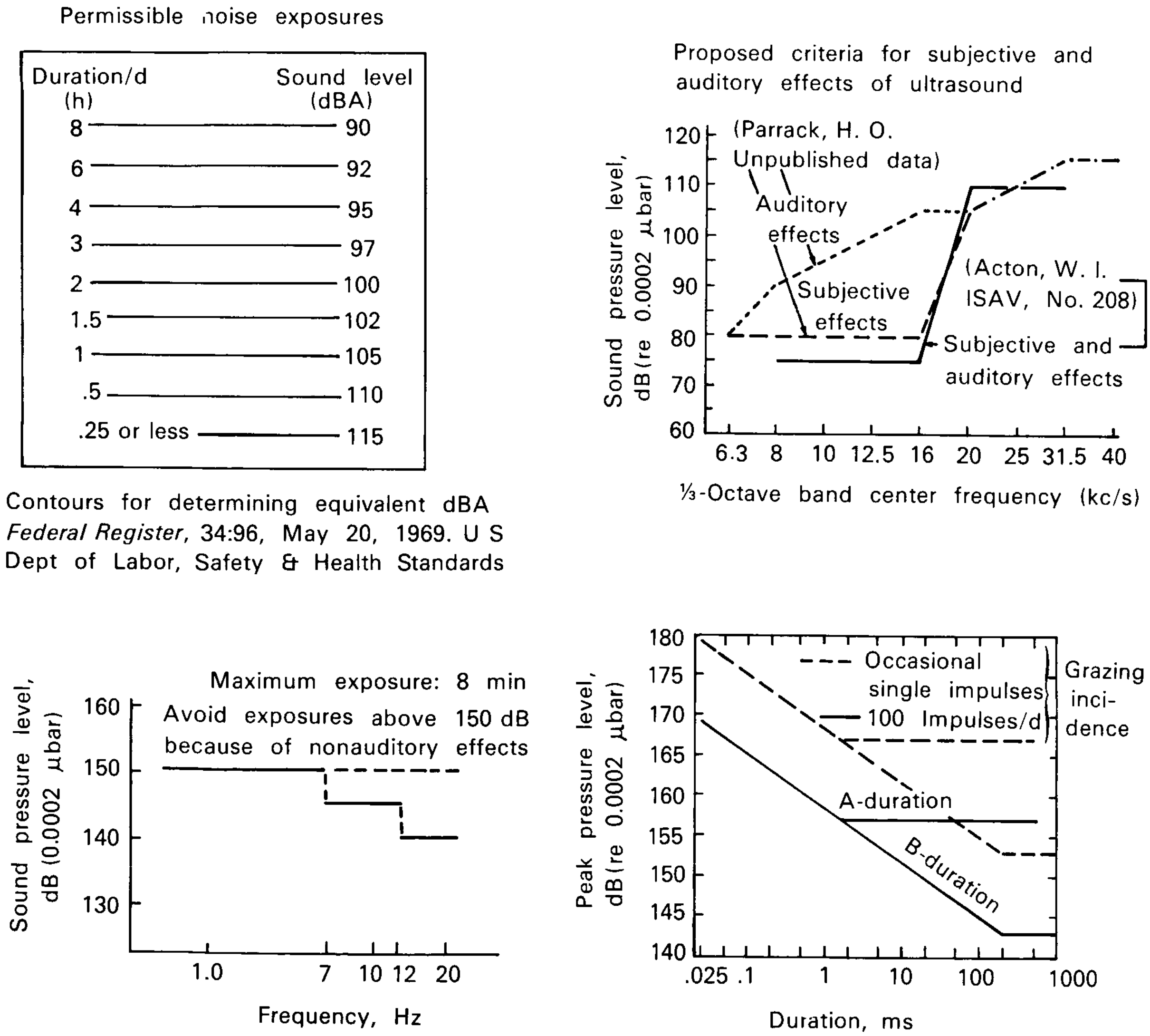

FIGURE 14.—Exposure guidelines for various categories of acoustic energy.

for this range for both discrete tones and octave bands is set at 135 dB for a single daily exposure of 20 min. This permissible level may be increased to 150 dB with the use of good earplugs for the same exposure duration. Again, the 150 dB maximum is intended to minimize nonauditory symptoms experienced by many individuals at these levels.

Audiofrequency

Range 100–6300 Hz. Damage risk for continuous exposure has been defined for up to 6 h by Borschevskiy [19] and for an 8-h workday by Kryter et al (CHABA) [74]. The limiting levels for typical workdays are considered compatible with unimpaired hearing for conversational speech signals after a work history of more than 10 years in the noise. Exposure criteria have been converted to equivalent A-weighted values in decibels (dBA) to simplify the measurement and assessment of noise-exposure risk. A-weighted values are currently in widespread use for noise monitoring purposes; however, for other purposes, such as engineering noise control, more detailed information about frequency content is essential.

Range 6300–20 000 Hz. Aerospace propulsion systems do not generate intense acoustic energy in this frequency range at locations occupied by personnel. Consequently, no limiting levels of noise are appropriate for rocket noise exposures. However, other aerospace sources may generate more intense energy in this region. Limiting values for subjective and auditory effects of ultrasound (determined independently by Parrack and Acton) are contained in Figure 14. There is good agreement among values for subjective effects; however, Parrack allows higher exposure levels from 6300 to 20 000 Hz than Acton does for auditory effects.

Ultrasound

Range above 20 000 Hz. Proposed criteria for energy in the frequency range above 20 000 Hz is also contained in Figure 14. Limiting effects in this inaudible range are confined to subjective symptoms such as malaise, headache, and fatigue. Compliance with the proposed values will greatly minimize adverse effects. Rocket propulsion noise in this frequency region dissipates rapidly and is not a problem. Personal hearing protective devices are very efficient against energy above about 8000 Hz. Use of these devices in ultrasound noise fields is usually sufficient to eliminate overexposure problems relating to hearing and to subjective symptoms of ill-feeling.

Impulse noise. Limiting noise exposure values for impulsive stimuli have been established and are presented in a form consistent with damage risk for continuous exposures in Figure 14 [15, 28]. Exposures which comply with these criteria should produce, on average, no more TTS than 10 dB at 1000 Hz, 15 dB at 2000 Hz, and 20 dB at 3000 Hz and above in 95% of the ears exposed. The curves represent criteria for a daily exposure of 100 impulses during any period ranging from 4 min to several hours. The criterion values are increased for fewer than, and decreased for more than, 100 impulses per day by a factor of about 1.5 dB for each doubling or halving of the number of impulses. In practice a 5-dB decrease in the allowable level must always be subtracted for those impulses which strike the ear at normal incidence.

Summary

Acoustic energy or noise is present in varying degrees from the time before launch of manned space missions until landing. In spite of the impressive quantity of work accomplished on the effects of noise on man, the noise problems of cosmic flight have not been fully resolved. Scientific knowledge coupled with the highly successful manned space programs of the USSR and the US provides the grounds for one to conclude, from a large base of objective evidence, that noise has not been a major limiting factor for space teams or the population through present generation systems and missions. Recommendations of permissible levels of noise for various phases of past missions have proved tolerable. Such levels, however, are not considered ideal and important questions concerning prolonged missions of many months remain to be answered.

THE VIBRATION FACTOR

Nature and Characteristics of Acoustic Energy

Vibration, in everyday language, means shaking, usually imposed by a mechanical agent such as the engine of a vehicle in which a person is riding, or by interaction between the vehicle and surface irregularities or air turbulence in the medium through which it moves. In physical terms, vibration may be defined [29] as a series of reversals of velocity, a process in which both displacement and acceleration necessarily take place. Disturbing vibration may reach man in several ways [50, 61]. It may affect man principally through a supporting surface such as an astronaut's or cosmonaut's couch; through some secondary contacting surface such as a headrest, sighting device, or control stick; through a fluid medium in which the body is immersed (akin to the acoustical transmission of noise through the body surface); or vibration may be disturbing indirectly, for instance, when the vibration of a space vehicle's instrument dials and pointers makes them difficult to read during launch. The chief descriptive parameters of vibration affecting man are frequency, intensity (amplitude), direction (with regard to the anatomical axes of the human body), and duration of exposure. A description of each follows.

Frequency. Frequency is an important descriptive parameter of vibration affecting man. The frequency of periodic (i.e., regularly recurring) oscillation is the number of complete cycles of motion taking place in a unit of time, customarily 1 s. The international standard unit of frequency is the hertz (Hz) which is 1 cycle/s.[2] Vibration in aerospace operations is often complex, irregular, or essentially random (e.g., the response of an airframe to turbulence) and consequently not obviously periodic in nature. Nevertheless, it is still possible and appropriate, with the application of spectral analysis techniques, to describe the motion in terms of frequency.

Amplitude. A second important characteristic of vibratory motion is its intensity or amplitude, i.e., the extent of the oscillation. When the vibration is a simple sinusoidal oscillation about a position of rest or equilibrium (the simplest kind of vibration), the amplitude is defined as the maximum displacement from that position. It is properly measured in meters but smaller metric units are often used for convenience.[3]

By extension, the term "amplitude" is commonly used with a qualifying word (e.g., "velocity-amplitude," "acceleration-amplitude") to describe the maximum or a related value of a vibrational velocity or acceleration. These quantities are determined by the frequency and the displacement-amplitude of a vibratory motion. In the case of sinusoidal vibration for which the frequency and amplitude are known, the corresponding values of velocity and acceleration may be determined with these simple formulas. Given the frequency, f, and the (displacement) amplitude, A:

$$\text{Velocity-amplitude} = 2\pi f A \qquad (1)$$

$$\text{Acceleration-amplitude} = 4\pi^2 f^2 A \qquad (2)$$

The same formulas apply approximately to narrow-band random vibration. Each successive time-derivative of displacement is obtained by an additional multiplication using the factor $2\pi f$; and the vibrational acceleration (a physiologically important parameter) corresponding to a given displacement rises with the square of the frequency of vibration.

A time-averaged or root-mean-square (rms) value of the intensity of a vibration must be computed, for example, when evaluating nonperiodic or complex vibrations. Many electronic vibration-measuring instruments yield an output proportional to the rms value of velocity or acceleration. In sinusoidal vibration, the rms value is $\sqrt{2}/2$ (0.707) times the maximum (peak) value. The relationships between sinusoidal vibration frequency, displacement, velocity, and acceleration are conveniently determined from the kind of nomograph shown in Figure 15 [50].

Directions and axes of vibration in man. The human response to a given vibration depends upon the point of application of the force to the

[2] This unit, cycle per second—c/s or cps—(replaced by Hz) is still in widespread use and commonly found in the literature on human response to vibration.

[3] In the English-speaking world, the inch (0.0254 m) remains in frequent use as the unit of displacement in vibration work.

body and the direction in which the force acts upon man. Directions of vibration entering the human body have received standardized definition [62] in relation to anatomical axes; the principal ones are illustrated in Figure 16. When evaluating vibration affecting man, the description of the vibration should apply to the force or motion at the point of entry into the body. It is important to beware of ambiguity which can arise, for instance, when vehicle vibration is measured at some point remote from man and is related to some frame of reference apart from the coordinate system of anatomical axes of the human body.

Time-course and duration of exposure to vibration. Human response is also influenced by the

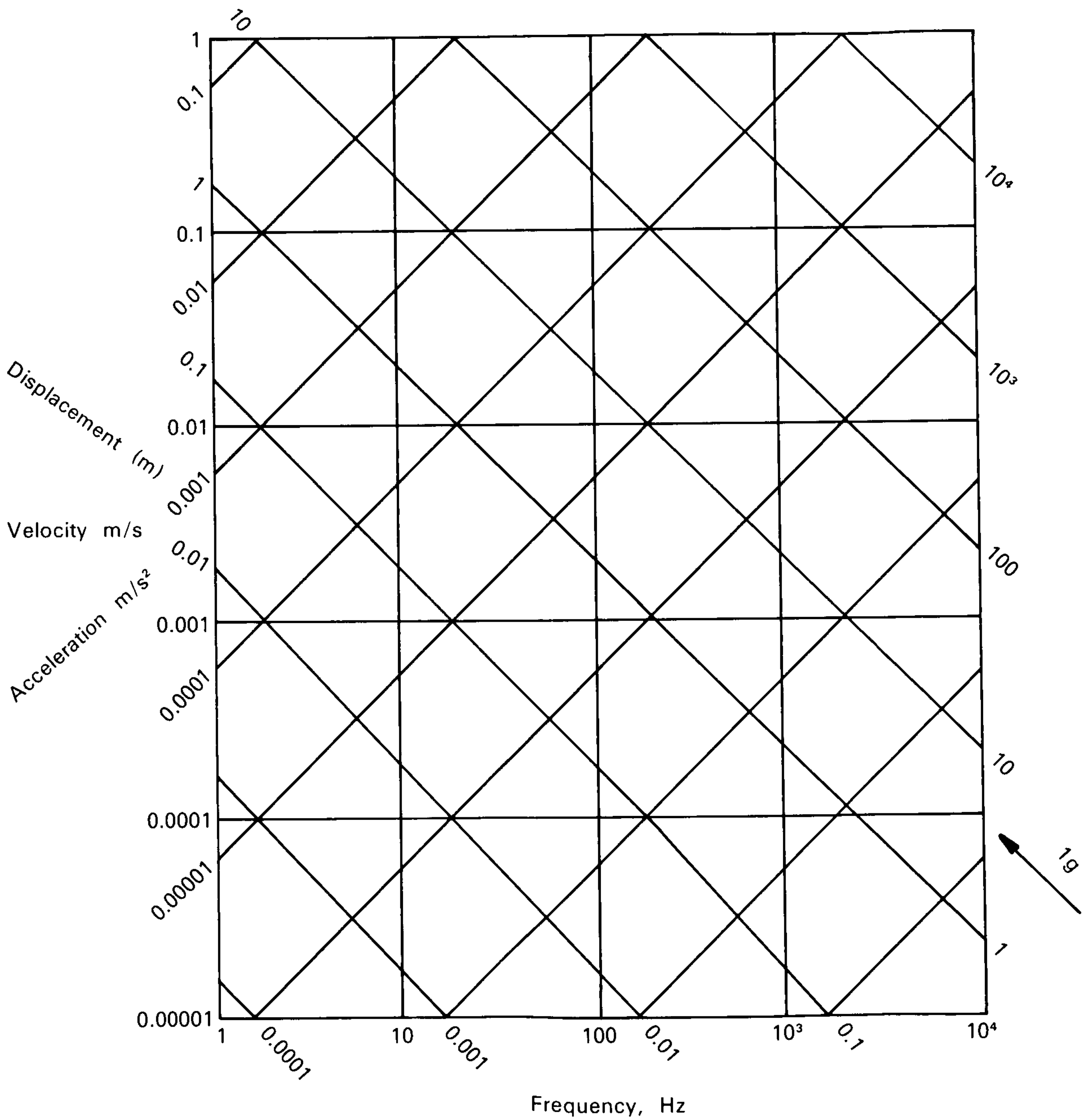

FIGURE 15.—Nomograph relating the principal parameters of sinusoidal vibration.

duration of exposure to a steady-state vibration or by the time course of a fluctuating or transient vibration. This aspect is considered in more detail in subsequent sections. In broad terms, human tolerance of continuous vibration declines with increasing duration of exposure [50, 61]. The extent to which this general tendency is mitigated by adaptation or habituation to vibration stress remains an open question, since little definitive research has been devoted to it so far. The expression, *long-term vibration,* is sometimes used (particularly in the US literature) to denote exposures exceeding 1 h. The corresponding expression, short-term (or short-duration) is not clearly defined but usually denotes exposures lasting 1 min to 1 h. Short-lived vibration, lasting for only a few seconds or a few cycles of motion, can usually be treated as transient vibration or shock motion.

Varieties of Vibration

The principal varieties of vibration observed in engineering practice are illustrated in Figure 17, showing representative waveforms and idealized spectra. Vibrations resembling these varieties can be experienced frequently in aerospace operations. The main distinction to be drawn is between deterministic and nondeterministic vibrations.

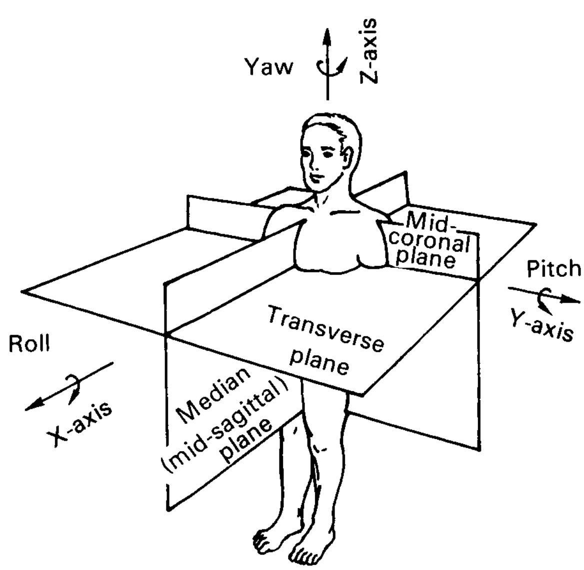

FIGURE 16. – Coordinate system used in biodynamics.

Deterministic vibrations. A deterministic vibration is one for which the magnitude of the displacement or its derivatives can be predicted for any instant from knowledge of its preceding characteristics (frequency, amplitude, phase angle). The simplest example of such a vibration is sinusoidal vibration, which has only a single frequency and, theoretically, a single line spectrum (see uppermost diagrams in Fig. 17). Although rarely encountered outside laboratory conditions, sinusoidal vibration is frequently approximated in practice (e.g., when a vehicle is vibrated by internal machinery running at a steady speed).

In many practical situations where machinery is running (e.g., space cabin conditioning equipment), complex harmonic vibration occurs. This is a deterministic vibration which can be regarded analytically as a mixture of two or more simultaneous sinusoidal vibrations. An example is in Figure 17(b). The lowermost component in the spectrum, called the fundamental, is not necessarily the most disturbing

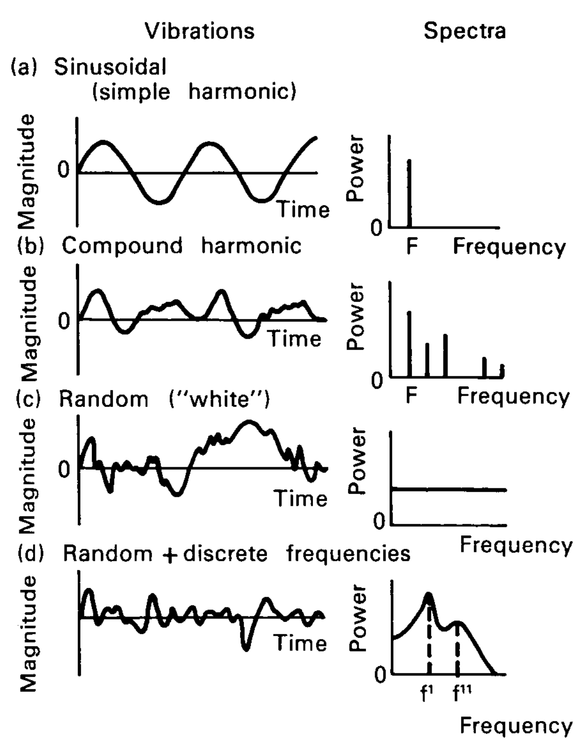

FIGURE 17. – Diagram of waveforms and idealized power spectra of typical varieties of vibration [50].

frequency component. The quality and biologic effect of such a vibration depend upon the relative, as well as the absolute, magnitude of each component and upon their phase relationships.

Nondeterministic or random vibration. When the vibration is irregular, lacking any recognizable periodicity, its time course is essentially unpredictable and is considered nondeterministic or, loosely speaking, random. Analytically, it has a continuous spectrum in which the energy of motion is distributed continuously and more or less uniformly over a range of frequency which can be of infinite extent. Certain sources of vibration, such as atmospheric turbulence, appear to be inherently random at source. When a vehicle with a flexible structure is subjected to random aerodynamic forces (e.g., during launch and ascent of a space vehicle), the crew is subjected to a composite vibration resembling that illustrated in Figure 17(d) [50]. In this case, one or more discrete frequency components, due to the aeroelastic response of the structure, are superimposed upon the essentially random input from the passing airstream.

Transient vibration and mechanical shock. When a vibrating system is subjected to an impulsive force or an abrupt displacement, the vibratory motion resulting within the system is typically short-lived (depending upon the amount of damping in the system) and may change rapidly with time before decaying to a negligible motion. Such a response is called transient vibration or shock motion (the latter term frequently connotes a relatively violent or potentially damaging response). Examples of transient vibration are the motions felt during separation of booster stages, during docking procedures in space, and upon impact with the ground or sea when a spacecraft returns to Earth.

Vibrating Systems and Resonance

Vibrating systems. Any mechanical system possessing the elementary properties of mass and elasticity can be set into internal motion by impressed forces. Engineering structures, such as buildings and airframes, and the living body are examples of such systems. Another essential property always present in any real system is damping, which is the physical process that opposes vibratory motion. Damping forces limit the vibration amplitude of a system subjected to maintained vibratory motion and bring a freely vibrating system eventually to rest. The system, if lightly damped (damping less than critical), will oscillate freely before achieving rest [50]. A lightly damped system, when forced to vibrate continuously at a characteristic frequency, is also capable of exhibiting resonance. In engineering and biodynamic practice, the value of damping in a system (including the human body) is customarily expressed as a fraction of the critical value.

Resonance. The simplest realizable vibrating system (a single mass, spring, and damper) is illustrated diagrammatically in Figure 18(a). The next simplest theoretical system is shown in Figure 18(b)—a two degree-of-freedom system. The characteristic response to forcing vibration as a function of frequency is illustrated to the right of each system. At a frequency or

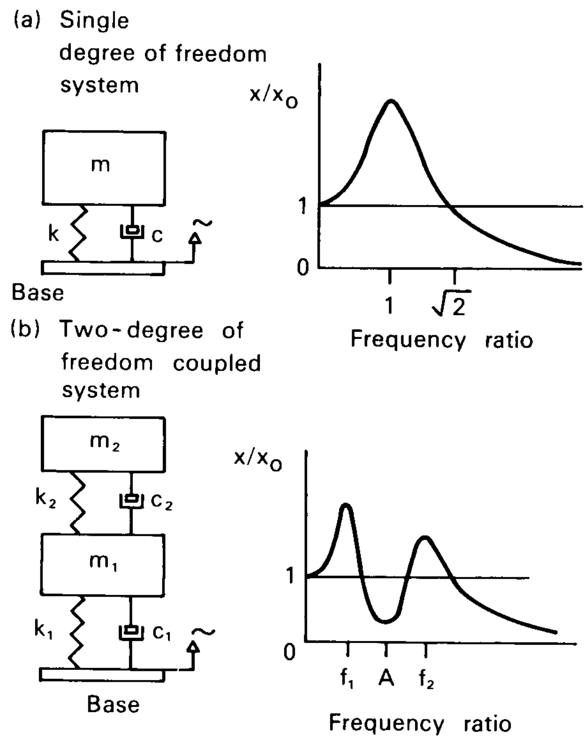

FIGURE 18.—Diagrams of simple vibrating systems and their responses to sinusoidal forcing motions applied to the base.

frequencies characteristic of any particular system, forcing vibration will elicit maximum response, i.e., maximum amplification of the impressed force or motion. It is said that the system resonates at that frequency. The degree of amplification at resonance is inversely related to the amount of damping in the system. The phenomenon of resonance, where relatively small forces at a critical frequency can sometimes excite large vibrations in a system, is often a nuisance in engineering and can be highly destructive. Much of the practice of vibration engineering is concerned with avoiding or suppressing resonance conditions. Biodynamic studies have shown that the human body is a complex vibrating system containing a number of resonant subsystems [36], some of which are illustrated diagrammatically in Figure 19. The characteristic response of man to low-frequency vibration in the z-axis [27, 35, 50] is illustrated in Figure 20.

The mechanical impedance of man determines the mechanical energy transmitted to the body in a vibration environment; consequently, it has recently been studied specifically with regard to the supine position (as in the astronaut's couch) and the simultaneous influence of sustained preloading accelerations of interest in current space operations [25, 133, 134]. Examples of responses observed under such conditions are in Figure 21. Such measurements and mathematical models have made it possible to predict changes in man's dynamic response to vibration in the weightless state—predictions, however, which still require verification from studies in space [133].

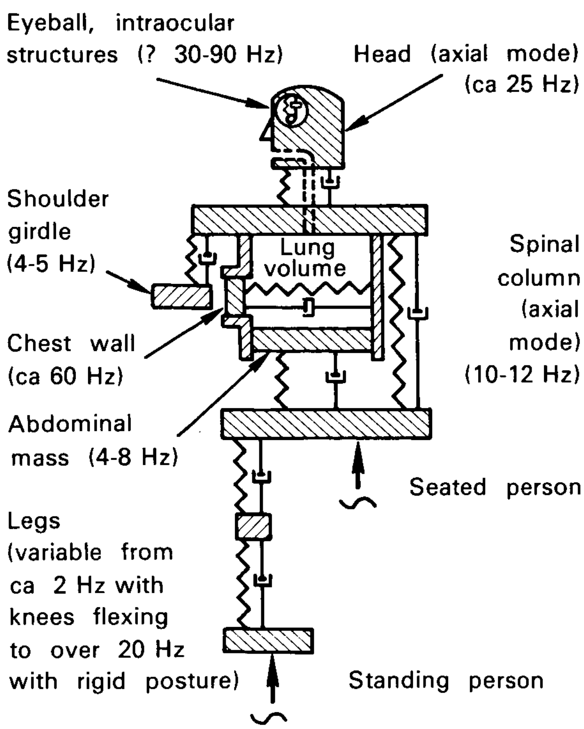

FIGURE 19.—Mechanical model (diagrammatic) of seated and standing man [35].

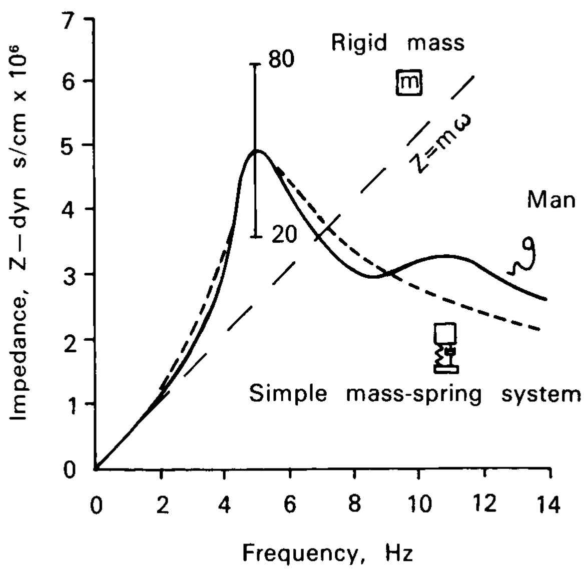

FIGURE 20.—Median z-axis impedance of seated male subjects [26].

Vibration in Space Operations

Appreciable vibration is often present during flight in aircraft and space vehicles [50]. In certain operations, it can be a serious nuisance and threat to the safety and health of the aviator or astronaut. Troublesome vibration during space operations can arise from prime movers (rocket engines), from aerodynamic causes, and from auxiliary-powered equipment running in space vehicles. At source, the vibration problems in space vehicles are of the same general nature as those in aircraft [50]; but space vehicle vibration may disturb the astronaut in substantially dif-

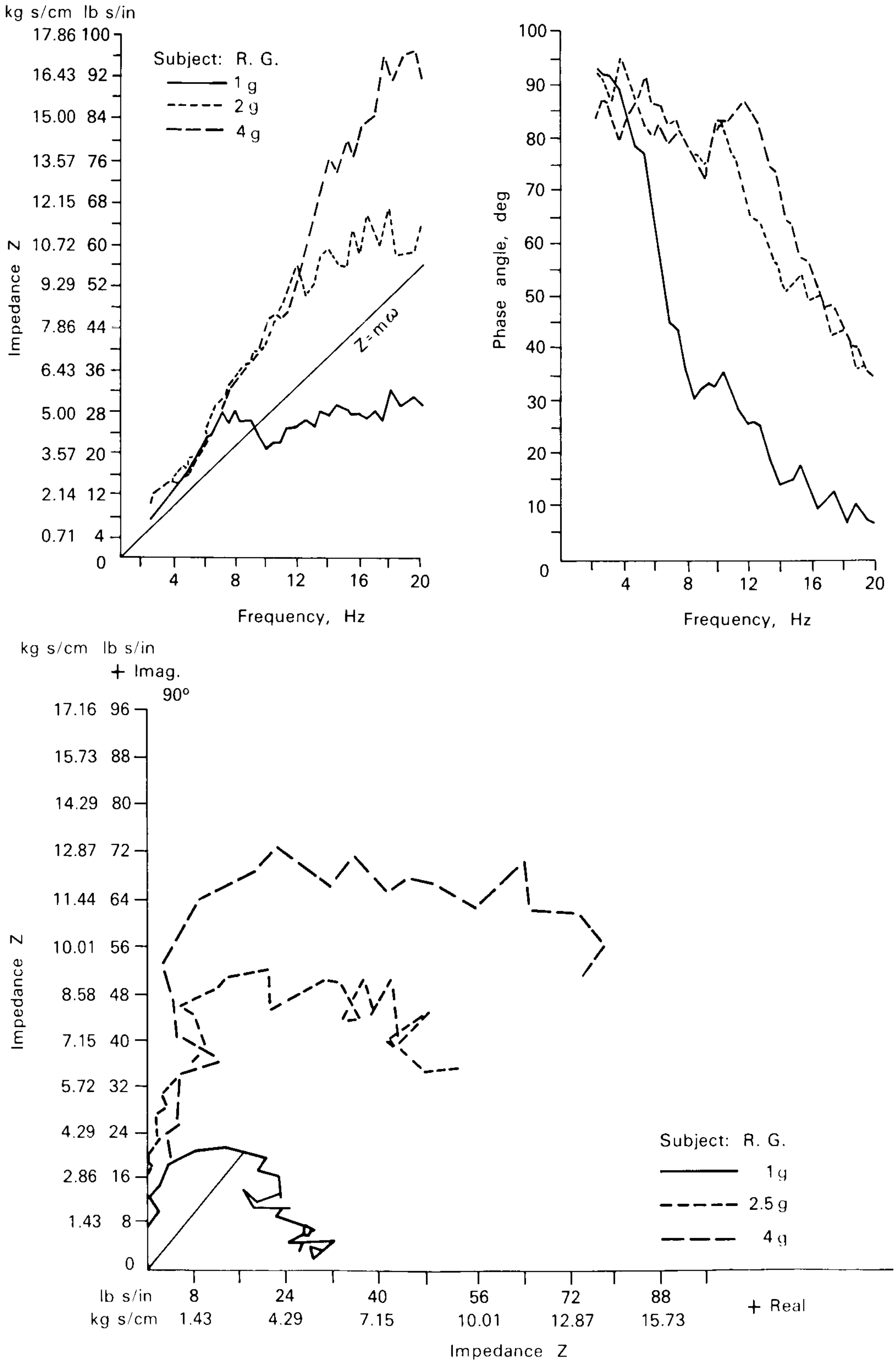

FIGURE 21.—Whole-body mechanical impedance under bias accelerations [134].

ferent ways and to varying degrees during different phases of a space mission.

Launch and ascent. When a large, multistage rocket vehicle carries man into orbit, intense distributed vibration enters the airframe of the vehicle and is transmitted to crew sites as vibration and noise. This vibration arises from the processes of combustion and the violent turbulence of the rocket exhaust. Low-frequency periodic vibrations, which can also disturb the astronaut in some vehicles, is caused by excitation of lateral bending modes and longitudinal ("pogostick") vibration of the vehicle structure. Such vibrations are induced by aerodynamic stresses of high-speed penetration of the atmosphere, rapid movement of fuel masses feeding the rocket engines, and operation of the flight guidance system. Transient oscillations are caused by impulses generated by starting up and burnout of the sequentially firing rocket engines in a multistage ascent, and by separation of stages. Major structural vibration frequencies in large spacecraft launching assemblies lie typically in the range 2–15 Hz [38].

Aeroelastically induced airframe vibration is worst during periods of transonic flight and maximum aerodynamic drag, which occur a minute or two after lift-off. After this maximal aerodynamic effect, the effect of the vehicle gathering speed is offset by the increasing rarefaction of the atmosphere. Changes in the pattern of vibration during ascent are also caused by loss of mass (due to consumption of fuel) and separation of stages. In some space vehicles, vibration during launch can be sufficiently intense to interfere with visual tasks such as reading instruments. The manner in which the astronaut is supported and constrained in a couch results in the vehicle vibration being transmitted to the whole body and to the head without attenuation normally provided by the upright body in the sitting position (as in an aircraft seat) [122, 128]. However, the increasing size and power of spacecraft launching vehicles is not necessarily accompanied by worsening vibration problems affecting the astronaut. Vibration during the launch phase in the recent US Apollo program was not apparently a serious nuisance, although noticeable by the astronauts [17].

Oribital and extended space flight. After the rocket engines have been shut down and the spacecraft is moving freely in a ballistic trajectory beyond the atmosphere, the primary sources of vibration (motors and aerodynamic forces) are absent. In the weightless state, the journey is subjectively motionless and essentially vibration-free. Vibration from secondary sources such as life-support equipment or other apparatus running in the spacecraft may, however, be noticed visually or upon contact with interior vehicle structures. Such vibration, even of low intensity, may be objectionable in some circumstances—when constantly or frequently present during extended space flights or long-duration orbital missions, or when the astronaut must perform a delicate task such as using an optical instrument.

Vibration in lunar and planetary expedition vehicles. The vibration problems in vehicles landing on, or exploring other worlds, remain largely hypothetical at present, although some problems can be anticipated [50]. Limited experience from lunar landings in the Apollo series revealed a vibration problem, minor so far, affecting vehicles of light construction standing on airless bodies. Astronauts on the Moon in the Apollo LEM vehicle occasionally reported that minor vibration and noise from equipment running in the module can be irritating and possibly interfere with rest and sleep during extended missions.

A peculiar problem can arise in connection with vehicle ride or with equipment vibration in vehicles standing on bodies with low gravity, such as the Moon or the planet Mars. Under reduced gravity, vertical vibrations of correspondingly lower intensity than required on Earth (± 1 g) are sufficient to lift an unrestrained rider from a vehicle seat, or shake objects loose from stowage. On the Moon, for example, vertical vibration with an acceleration-amplitude of only 0.11 g_{rms} will be intense enough to cause such an effect. The phenomenon has a bearing on the design of suspension and restraint systems for surface vehicles intended to ride on bodies lighter than the Earth, and on the stowage of loose objects likely to "walk" due to vibration from nearby running equipment.

Reentry and recovery. Vibration during return to Earth does not appear to be a problem with current techniques, although the superimposition of severe, if short-lived oscillations upon the deceleration pulse has been anticipated in the case of flight instability developing during reentry of a ballistic vehicle [66]. This may be a renewed problem in some circumstances during reentry and descent of winged aerospace vehicles of the space shuttle type, which, after ballistic reentry, are flown to the ground as aircraft under the guidance of a human pilot.

One problem after landing is seasickness, peculiar to recoveries at sea—currently the practice in the US manned spaceflight program. This can trouble an astronaut left floating in the spacecraft in a choppy sea for too long before being extricated; for this reason, anti-motion sickness remedies are customarily carried. However, the problem would appear to be lessening with the increasing precision and speed of recovery procedures.

Vibration of ground and buildings during space operations. Heavy groundborne vibration, in addition to intense broadband noise, can be radiated over great distances when a large space vehicle is launched or when giant rocket engines are tested in captive-firing installations. Other installations and buildings in the surrounding area, up to several kilometers away, are set into low-frequency vibration by the combustion and exhaust noise of the rocket engines, which shakes the ground directly and is propagated acoustically as intense atmospheric waves. Buildings and exposed personnel can be affected by both routes of transmission. Attenuation by distance is the principal means of dealing with the problem.

Effects of Vibration on Man: Biodynamics

The physiologic and psychologic effects of vibration in man are caused by vibratory deformation or displacement of the organs and tissues of the body, so as to disturb their normal function and excite the distributed mechanoreceptors which mediate the vibration sense [47, 50]. Vibration also acts in a purely mechanical way to force differential motion to take place between man and his points of contact with tasks or his points of reference in the external world. The body is a complex vibrating system capable of resonance, so that many biologic actions of vibration are strongly frequency-dependent. From a biodynamic viewpoint, the frequency spectrum of mechanical vibration affecting man can be divided into two main regions: low-frequency and high-frequency responses [41, 49, 50].

Low-frequency response: body resonance phenomena. Human body resonance may be defined as the condition where a forcing vibration is applied to the body at such a frequency that some anatomic structure, part, or organ is set into measurable or subjectively noticeable oscillation of greater amplitude than that of related structures [50]. It may be studied by direct observation and by mechanical impedance and transmissibility techniques [27, 35, 50]. The body can be visualized, and modeled analogically, as a complex vibrating system with many degrees of freedom (Fig. 19). A lumped-parameter approach is appropriate to its modeling at frequencies below 50 Hz [36, 41, 109]. The excitation of particular modes of vibration in man by continuous vibration or by impact forces depends to a great extent upon the direction of vibration and upon such other physical factors as the person's size, build, posture, and degree of tension in the skeletal musculature [50]. Body resonance can also be influenced by external restraints and loads applied to the person and by dynamic interactions between the body and resilient supports, such as a springy seat.

Extensive work in the US and elsewhere has established that the principal resonance of the seated, standing, or recumbent human body vibrated in the z-axis occurs at a frequency of 4–5 Hz, and that this response is reflected in the frequency-dependence of many physiologic and psychologic human reactions to whole-body vibration [27, 35, 50, 61]. The same response is also a major factor governing the frequency-dependence of human voluntary tolerance of severe z-axis vibration [89]. The anatomical basis of the resonance is complex and not yet entirely clear. At least two major anatomical systems may be involved (depending on the degree of restraint)—the thoraco-abdominal system (the principal controlling element) and the pectoral girdle.

A second important resonance in man subjected to z-axis vibration or impact occurs in the region of 12 Hz, which can be demonstrated as a local impedance maximum (see Fig. 20) or as a phase resonance [27, 50]. This resonance appears to be associated with axial compression of the torso and to be controlled by the elastic properties of the spinal column and its associated musculature. It is of significance mainly in relation to human tolerance of severe z-axis impacts and cumulative long-term exposure to z-axis vibration such as in rough-riding vehicles. Other resonances of smaller structures are excited by vibration at higher frequencies, some of which are illustrated in Figure 19.

When man is vibrated in the x- or y-axis, typically by horizontal vibration of a seat or of a floor upon which he is sitting or standing, the principal resonance occurs in a new mode—a body-bending mode at 1–2 Hz. Accordingly, x- or y-axis vibration is most disturbing at such frequencies, in contrast to z-axis vibration, which is most disturbing at about 5 Hz. These differences in the human dynamic response are reflected in the subjective response and in the effects of vibration upon performance. The influence of vibration direction upon the human frequency-response to vibration is, in general, of sufficient magnitude to require different exposure limits [50, 61].

Nonlinearity and biasing accelerations. The amplitude response of the body to z-axis vibration at frequencies around the principal resonance (5 Hz) appears to be fairly constant up to acceleration amplitudes of the order of 0.5 g [49] but somewhat reduced at higher acceleration levels for both z- [26] and y-axis vibration [59]. Some nonlinearity may be accounted for by involuntary muscular tensing during severe vibration at low frequencies.

In certain circumstances, men are vibrated while simultaneously being subjected to acceleration or altered gravitational conditions. During space flight, body weight is altered by the forces of launch and reentry; weightlessness supervenes during orbital and interplanetary flight. Reduced gravity acts when the astronaut is standing or riding upon a lighter body such as the Moon or in the synthetic gravitational field of a rotating space station. Most studies of the human biodynamic response to vibration have, of course, been carried out in Earthbound laboratories, where the body responds under the normal force of gravity. Some recent work, however, has shown that, when man is subjected to accelerations greater than gravity, his biodynamic response to vibrations applied simultaneously in the same direction (the z-axis) is altered. Under accelerations of up to $+4\ G_z$, impedence measurements during z-axis vibration in the range 2.5–20 Hz have shown that the acceleration compresses and stiffens the body so as to raise the resonant frequencies of man and possibly introduce new resonances [133, 134].

High-frequency response: wave propagation in the human body. At frequencies above about 50 Hz, the response of the human body to impressed vibration can be visualized as that of a continuous viscoelastic medium of propagation rather than as a lumped-parameter system [41]. As the frequency rises into the kilohertz range, the propagation of vibration within the body tissues progressively becomes increasingly acoustical in nature, i.e., at high frequencies, most of the vibratory energy entering through the body surface is propagated through the tissues as compressional waves.

Physiologic Effects of Vibration

Physiologic effects of vibration fall into two broad categories [49, 50]. In the first are those responses attributable directly to the differential vibratory motion or deformation of the organs or tissues of the body. Such responses are mainly frequency-dependent and can be related to body resonance phenomena. In the second category of response to vibration are nonspecific generalized reactions, i.e., reactions to stress in general, not specific to the physical nature of vibration. The latter reactions are not markedly frequency-dependent, and appear to be related predominantly to the overall severity of the vibration exposure and its cumulative duration.

Systemic Effects of Whole-Body Vibration

Cardiopulmonary responses. Whole-body vibration of moderate intensity (above about 0.1 g_{rms})

induces the vegetative manifestations of alarm or mild exercise, with increases in heart and respiratory rates, pulmonary ventilation, and oxygen uptake [49, 50]. Such changes are associated with raised metabolic activity due to increased activity in the skeletal musculature in maintaining the posture during vibration, but other reactions are evident during severe vibration. Under certain conditions, strong whole-body vibration can induce hyperventilation, which is probably due to a centrally mediated reflex response to the widespread vibratory stimulation of somatic mechanoreceptors, including those in lung and the respiratory passages [30, 50, 77]. The response exhibits features of a classical (Pavlovian) conditioned reflex response to a strong environmental influence; it can be blocked in man by light general anesthesia [77]. A pronounced hyperventilatory effect in man, with symptoms and signs of hypocapnia, can be produced by a few minutes of z-axis vibration at acceleration-amplitudes above 0.5 g in the range 1–10 Hz [31].

Cardiovascular responses during vibration. Increases in heart rate are commonly observed in animals and man during whole-body vibration at infrasonic frequencies, but the magnitude and time course of the response are highly variable between subjects and with the prevailing heart rate before vibration [50, 57, 112]. Heart rate changes during vibration are not necessarily correlated with changes in blood pressure [24, 57]. As a rule, however, increases in heart rate, cardiac output, and arterial blood pressure which are observed resemble those in response to moderate exercise [57] or alarm [34]. Local vibration of hands or feet can induce peripheral vasoconstriction, with restriction of blood flow in the extremity. A Soviet investigation [67] has shown that this action can be opposed or abolished by warming the same part.

Metabolic and endocrinological effects. Various changes in cellular and biochemical constituents of urine and blood have been observed in animals and in man in response to sustained low-frequency, whole-body vibration. In general, these changes appear to reflect a nonspecific response to the stress [11, 49]. Certain endocrinological changes in animals, involving the adrenal, thyroid, and other endocrine glands [108] appear also to be a generalized stress response. The question of protein and carbohydrate metabolism and metabolism of certain vitamins has attracted considerable interest in the Soviet Union and elsewhere. Animal and human studies have revealed mild disorders or abnormalities of various metabolic indices in response to occupational-type vibration stress [10, 18, 67, 75, 84, 108, 110, 130, 139, 140].

Sensory and Neuromuscular Effects of Vibration

Sensory mechanisms. Mechanical vibration is perceived over a much wider range of frequency than is occupied by the sensation of hearing; more than one kind of receptor organ is involved [47, 49, 50]. Mechanoreceptors of the body respond to vibration in various overlapping frequency ranges, differing both in the effective bandwidth of their response and the degree of temporal integration of information they transmit to the brain. The principal vibration-sensing organs in man are the cutaneous receptors subserving the vibrotactile sense [93, 98], the mechanoreceptors distributed in deeper structures (especially muscles, tendons, joints, and the visceral organs and their attachments) [50, 93], and the vestibular organs [14, 50].

Effects of vibration on muscular and postural mechanisms. Several studies have related increases in manual or digital tremor or postural sway of the standing person to heavy regional or whole-body vibration in the 1–100 Hz range [50, 80, 81, 94]. Some workers have postulated that such effects are due to vibratory overstimulation of the receptors and to competition in the neural pathways subserving both postural regulation and the low-frequency somatic and vestibular vibration sense. However, similar responses (especially increased digital tremor) are observed under other conditions, and the effects are not necessarily specific to vibratory stimulation. Increases in sway and tremor can be observed in states of high arousal and in fatigue associated with sustained, high workload and environmental stress not accompanied by strong motion stimuli [102].

Mechanical vibration of the whole body or of individual postural muscles or their tendons elicits tonic reflex contraction, while phasic spinal reflexes (e.g., tendon jerks) sometimes appear to be depressed or inhibited. These phenomena, observable over a wide range of vibration frequency from around 10 to over 200 Hz, have been studied in man as well as in animals (including decerebrate preparations) [50]. The tonic reflex contraction is mediated by vibration-sensitive receptors in muscle itself, chiefly (but not solely) the primary spindle endings [92]. The response, apparently mediated by a polysynaptic pathway involving higher centers including the cerebellum, can be influenced by various factors operating supraspinally. Moreover, some degree of voluntary inhibition can be achieved [91].

Local low-frequency vibration of postural muscles in man does not appear to alter the reflex excitability of the muscle, nor the character or strength of the maximal volitional response [52], at least in short-term exposures. Soviet work, however, in examining the occupational hazard of prolonged exposure to the vibration of hand-held power tools, indicates that some kinds of vibration exposure may lead to alterations in peripheral neuromuscular function in the long term [22, 76, 88, 127].

Effects of vibration on the central nervous system (CNS). Qualitative observations suggest that vibration can alter the level of arousal in various ways (as can noise), depending upon the physical characteristics of the vibration and nature of the subject's activity at the time of exposure. Low-frequency (1–2 Hz) oscillations at moderate intensities can be soporific in man, while stronger vibrations, higher frequencies, and inconstancy of the stimulus are arousing. A considerable degree of adaptation or habituation to steady-state vibration (e.g., the drone of aircraft or shipboard vibration) can be achieved, provided the stimulus is not changed or interrupted. Habituation to vibration is probably a central phenomenon, although some adaptation may occur at the receptor level. Central factors appear to play a role in the reactions of animals to extreme vibration stress. The lethality of intense whole-body vibration (± 10 g at 25 Hz) in mice is enhanced by centrally acting stimulants (dextroamphetamine) and reduced by central depressants (chlordiazepoxide; reserpine; barbiturates) [12]. Animal studies conducted in the Soviet Union showed that vibration stress responses include fluctuations in the oxygen uptake of cerebral tissue [85]. In man, industrial vibration stress may be associated with nonspecific alterations in function of the CNS, possibly contributing to industrial fatigue and affecting occupational health [9, 95, 124]. Soviet work has also indicated possible synergistic effects between the actions of vibration and other physical agents on the nervous and endocrine systems. Such agents acting in combination with vibration include noise [9, 90] and ionizing radiation [79].

Motion sickness. Motion sickness (kinetosis) is primarily a response to varying acceleration or to oscillations in the frequency range 0.1–1 Hz [50], but the response depends heavily upon conditioning in man. Motion sickness associated with space flight is dealt with in Volume II, Part 2, Chapter 4, and will not be considered further here.

The electroencephalogram (EEG) and other electrophysiological recordings during vibration. The EEG [4, 101], electrocardiogram (ECG) [111], and electromyogram (EMG) [52] can all be recorded in man during vibration. Sufficient care must be taken however, in the selection and placement of instrumentation in order to guard against vibratory motion artifacts in the recording. The nature of the synchronous activity recordable at frequencies related to that of vibration in the EEG remains an open question [50, 101]; it has been contended that vibration evokes synchronous neuronal activity in certain brain structures [4] but such activity is difficult to distinguish from recording artifacts. Abnormal EEG recordings can be observed during vibration stress as the result of indirect physiologic mechanisms, such as hyperventilation or fluctuations in the oxygen metabolism of the cerebrum [85]. Ursoniu et al [131] have reported EEG changes of uncertain significance, following occupational exposure to hand-transmitted vibration in workers using pneumatic hammers.

Psychologic Effects of Vibration

Several substantial reviews of the subjective and performance effects of vibration have been published in recent years [49, 50, 58, 115, 121]. Accordingly, only a brief summary of the principal psychologic effects of vibration on the organism will be given here.

Subjective Reactions

Subjective reactions to vibration depend greatly upon individual sensitivity and upon the circumstances in which the vibration is felt [54]. While vibrations just above the threshold of perception may be objectionable in some situations (e.g., in an orbiting observatory), quite severe levels may be tolerated for a short time when the motion is, so to speak, *natural* to the situation (e.g., during the launch phase of a space mission). It is therefore very difficult, if not practically impossible, to establish simple or universally applicable limits of vibration according to subjective criteria, even in so restricted a field as astronaut comfort. Nevertheless, extensions of the concept of *reduced comfort* [61], and the tentative limits which have been drawn up according to that criterion, will serve as a guide in this connection.

Subjective rating and psychophysical estimation of vibration. Numerous attempts have been made since early in the 20th century to establish sets of curves of equal disturbance or discomfort due to vibration for the purposes of ride engineering in various branches of transportation [20, 47, 49, 50, 53]. These attempts have made use mostly of empirical, verbally structured rating scales. Such methods have important drawbacks, such as difficulty of standardizing meaning (even in the same language) and hierarchical relationships of such terms as "disturbing," "disagreeable," "uncomfortable," "alarming," and so on. Moreover, there has been little agreement between investigators regarding the end point of human acceptance of vibration in subjective experiments [50]. End points have, for example, included the appearance of physical symptoms, reluctance to continue vibration for unspecified reasons, and interference with a specific activity such as reading.

Psychophysical methods using such techniques as vibration magnitude estimation and intensity matching have, in recent years, shown considerable promise, enabling the construction of equal-sensation contours for vibration analogous to equal-loudness contours for noise [50, 96, 123]. This approach assumes that the growth of vibration sensation magnitude obeys a power law of stimulus intensity of the same general type that Stevens has demonstrated for other modalities of sensation. Thus, Stevens' scaling methods accordingly are assumed appropriate to whole-body vibration intensity judgments—as indeed they have been shown for cutaneous vibrotactile sensitivity [132].

Figure 22 shows a comparison between data obtained by Shoenberger and Harris [123] using intensity matching and magnitude estimation techniques during z-axis whole-body vibration of men in the frequency range 3.5–20 Hz. There is satisfactory agreement between the results from each method, which show the de-

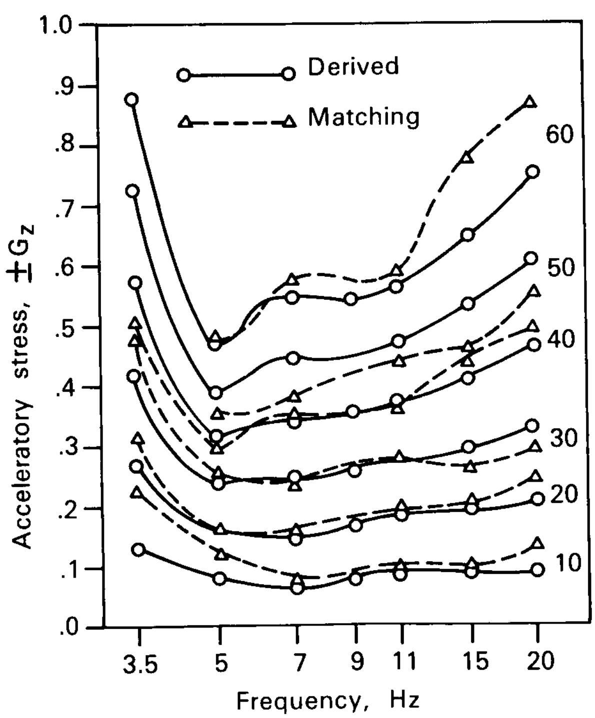

FIGURE 22.—Intensity matching and equal subjective magnitude curves for z-axis whole-body vibration of seated man [123].

pression of thresholds at frequencies in the region of 5 to 10 Hz. This phenomenon becomes more pronounced as the level of vibration is increased and at high intensities (about 0.5 Gz and above), these data accord well with earlier work [89] on the limits of voluntary tolerance of *z*-axis vibration.

There has been little work so far on dual frequency or other composite vibrations [50, 61], but from recent studies of subjective responses to low-frequency compound harmonic vibration, it appears that a form of sensory masking can occur [21, 82] where the presence of one sinusoidal component can alter the threshold for another.

In the dynamic range of human sensitivity to vibration, again, there have been few reliable determinations of human thresholds of sensation for oscillatory motion. These determinations are rather difficult to make, since it is technically difficult to achieve acceptably pure vibration of the whole body at threshold levels and to screen the subject from sensory cues to motion other than the vibration sense in question. Various observational and experimental evidence, however, shows that the human threshold of perception for rectilinear whole-body vibration in the range of 0.1–10 Hz is remarkably low—of the order of 0.01 m/s^2 (or about 1/1000 g) [47, 50]. The threshold for rotational oscillations at frequencies below 1 Hz is approximately $1°/s^2$ for motion about the z-axis and may be substantially lower in some subjects [23].

At the other extreme of the range of vibratory sensation, the threshold of pain or gross bodily discomfort during short-term human exposure to whole-body vibration in the 1–10 Hz range is approximately 10 m/s^2 (about ± 1 g) [89]. Thus, the dynamic range of normal human sensation of whole-body vibration in the most sensitive frequency range is approximately 60 dB, which contrasts with a range of some 130 dB for audible sound perceived by the ear.

Effects of Vibration on Performance of Tasks

Heavy vibration or oscillatory motion of man can affect the performance of tasks in several ways [42, 43, 50, 58, 115, 121]. First, vibration of man or of the elements of his task makes it more difficult to comprehend visually presented information; second, vibration disrupts precise movements, particularly of the arm and hand. Flight experience [50], as well as some laboratory experiments, show that heavy low-frequency vibration can also degrade performance centrally, acting in a nonspecific way as a distracting and fatiguing agent, as does noise [48], but such a mechanism is not easily demonstrated by experiment. Moreover, caution should be exercized when interpreting experimental results that appear to show central or time-dependent effects of vibration upon performance, for the effects in question may not be the result of mechanical influences alone. The effect of environmental stressors such as vibration and noise is governed by numerous psychologic factors not necessarily related to the nature of the agent; when stressors are acting in combination, which is frequent in aerospace operations, the effect is not necessarily simply additive—some combinations may act synergistically, others antagonistically upon performance [42, 50, 55, 63, 137].

Experience from flight tests and flight simulation. A substantial amount of insight into the effects of turbulence encounters and aircraft vibration upon performance of tasks by aircrew has been gained from flight experience and experiments in dynamic flight simulators [50, 78]. In summary, aircraft motions in response to external sources of vibration occur mainly at frequencies below about 2 Hz, and are associated by aircrew with:

- discomfort and progressive fatigue
- increased effort by pilots to avoid or correct inadvertent control movements
- difficulty in using navigation instruments
- difficulty in interpreting flight instrument information
- disorientation, occasionally.

Higher frequency (2–10 Hz) airframe vibrations are associated with:

- difficulty in reading instruments or carrying out other tasks calling for final visual discrimination (e.g., visual search, reading CRT display) interference with some manipulative tasks (e.g., writing, setting cursors on hand-held navigation aids)

general discomfort and progressively worsening fatigue on long missions.

Kindred problems may be anticipated in certain phases of space flight, such as descent through the atmosphere of space shuttle-type vehicles which are flown as aircraft.

Laboratory studies of performance during vibration. Current guidelines for preserving human operational efficiency during whole-body vibration [61] are based largely upon studies of human performance decrements measured during exposure to vibration on laboratory machines. These experiments have been mainly short-term studies showing strongly frequency-dependent effects of low-frequency (1–30 Hz) vibration upon the performance of visual and psychomotor tasks. In relation to manned space flight, these effects are most likely to be important during a mission's launch and reentry phases. Laboratory research into the effects of vibration on visual and psychomotor performance (the threshold for impairment of which is an acceleration-amplitude of the order of 1 m/s^2 (± 0.1 g) in the 1–10 Hz range) has been reviewed extensively in many other publications [42, 50, 58, 60, 115, 116, 121, 122, 128].

Effects of vibration on verbal communication. Human speech can be markedly distorted or interrupted by heavy vibration or jolting of the speaker. This can add to communication difficulties in some phases of space flight, particularly when high levels of masking noise are also present.

Whole-body vibration of speakers at frequencies below 20 Hz, and especially in the range 4–10 Hz, degrades the quality and alters the pattern of human speech, depending upon the speaker's posture and the direction, intensity, and periodicity of the vibration [103, 104, 105]. Within the critical range of frequency, intelligible speech becomes increasingly difficult to maintain as the level of whole-body vibration is increased above about 0.3 g_{rms}. Intelligibility under such conditions can be helped somewhat by maintaining an adequate speech level (speech/noise ratio), by training speakers and listeners to communicate in the presence of vibration-modulation of the speech, and, possibly, by the use of restricted vocabularies for such communication. Whole-body vibration at infrasonic frequencies, even at severe levels, does not appear to have a significant effect upon hearing [51].

Pathologic Effects of Vibration

Intense vibration can cause pain and injury in the living body [50]. Acute traumatic effects, dependent primarily upon the intensity and the frequency of the vibration, are most likely to occur when severe vibration is applied to the unprotected body at frequencies related to the principal system and organ resonances. Long-term or repeated exposure to moderately severe but not immediately damaging levels of vibration can also be a hazard in certain pursuits and occupations, such as driving rough-riding vehicles [114] or flying strongly vibrating helicopters [119]. In such situations, the effect or cumulative duration of exposure to the stress appears to be a primary factor governing the development of injury or disease.

Severe acute whole-body vibration exposure. Animal studies on the lethality of severe whole-body vibration (in the range 1–20 g at 1–50 Hz) have shown that intense shaking causes hemorrhagic injury to many of the soft organs in the body. Roman [113] has shown that in mice, the lethality of whole-body vibration is strongly frequency-dependent (Fig. 23), being greatest at frequencies associated with the main thoraco-abdominal resonance. The most common pathologic changes in small animals killed by vibration are hemorrhagic damage to lung parenchyma and myocardium and bleeding into the gastrointestinal tract. Superficial hemorrhage of the brain and kidneys has been less common. There is some evidence that endocrinologic factors (particularly the level of male hormones) may predispose animals to lethal vibration stress [117, 118]. Lethality may also be influenced by other physical agents acting at the same time as the vibration, such as ionizing radiation and hypoxia [86]. Based on animal experiments, the pattern of injury with acute

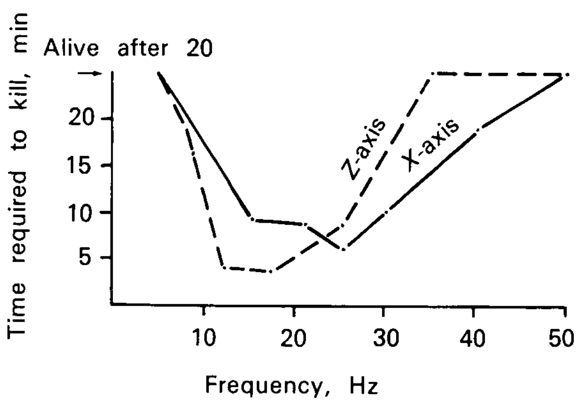

FIGURE 23.—Effect of frequency of vibration on average time required to kill mice [113].

human exposure to injurious levels of whole-body vibration would resemble that resulting from impact accelerations of comparable severity. The probable mechanisms of injury include tearing of the suspensory ligaments and integuments of organs violently displaced at their resonance frequencies within the body and, during severe z-axis oscillation, compressional injury to the spine.

Chronic human exposure to vehicle vibration. Occupational disorders involving the spine and internal systems have been associated clinically with continued exposure to the rough motion of certain types of vehicles, including agricultural tractors and some kinds of aircraft (helicopters) [50, 114, 119]. The etiology of these disorders is not yet clear and may be complex. Certain factors in addition to the vibration exposure, for example, climatically adverse working conditions and bad ergonomic factors in the design and construction of the vehicle, may be equally important. The extent to which chronic exposure to moderate levels of whole-body vibration can injure the otherwise healthy body remains an open question. Disease due to such chronic exposure is not likely to be a problem for the astronaut, because injurious levels of vibration, if occurring at all, are not maintained in space vehicles for prolonged periods.

Although hand-transmitted vibration is an occupational hazard to workers with power-driven tools in industry [9, 50, 90], it is not a serious problem in space flight at present.

Criteria and Limits of Human Exposure to Vibration

Setting limits of safe or acceptable human exposure to vibration has been attempted many times. Until very recently, however, guidance for the engineer in this area has been confusing and frequently conflicting, because of the multiplicity of guidelines published for different purposes and widely varied criteria of protection [20, 50, 53, 58]. The International Organization for Standardization (ISO) has therefore attempted to unify guidelines for criteria, methods of physical evaluation, and acceptable limits of human exposure to vibration. Their recent work [4] has led to formulation of an international standard on evaluation of human exposure to whole-body vibration in the range 1–80 Hz [61]. Their standard is currently in process of adoption as a national standard in several countries, including the US. Previously, only the Soviet Union [87] had adopted a national standard or regulation governing human vibration exposure in workplaces.

The ISO recommendation [61] recognizes three basic criteria for limiting human exposure to vibration and gives advisory limits accordingly. The criteria (and corresponding limits) are:

Preservation of health or safety ("Exposure Limit")

Preservation of working efficiency or performance ("Fatigue-decreased Proficiency Boundary")

Preservation of comfort ("Reduced Comfort Boundary").

Certain values of the Fatigue-decreased Proficiency Boundary for x-, y-, and z-axis vibration are shown in Figures 24 and 25. Corresponding values for the Exposure Limit are obtained by a multiplication of 2 (doubling the values in Figs. 24 and 25) and for the Reduced Comfort Boundary by dividing the values for the Fatigue-decreased Proficiency Boundary by 3.15 (equivalent to a reduction in acceptable vibration level of 10 dB). Figures 24 and 25 also illustrate the

[4] ISO Technical Committee 108 (Mechanical Vibration and Shock), Subcommittee 4 (Human Exposure to Mechanical Vibration and Shock).

allowance made for daily duration of exposure in the evaluation of vibration affecting man. These limits are tentative, remaining subject to revision and refinement of the standard pending new and better data available on the human response to vibration in the future [37, 46, 61].

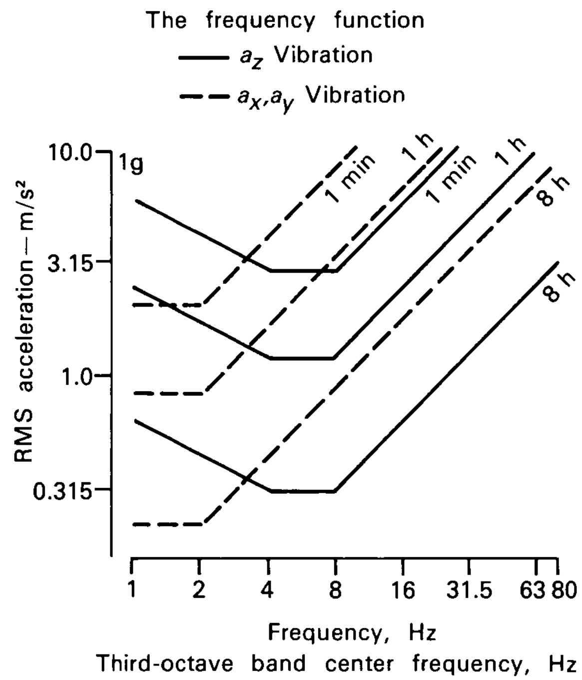

FIGURE 24.—Proposed ISO "Fatigue-decreased proficiency" boundaries (the frequency function) [61].

The ISO vibration exposure standards provide appropriate guidance for average routine vibration exposures of the general population and for normal occupational exposures. The guidelines must be modified for space operations, however, for several reasons:

- a special supine (couch) position is used in space flight for the advantages that it tends to provide in sustained acceleration tolerance;
- an optimized support and restraint system is provided for astronauts;
- astronauts are a special population, selected specifically for their physical fitness and training to undergo the stresses of space flight, and their exposure to severe vibrations is limited to a brief period during their infrequent space missions (i.e., it is not a prolonged, daily occupational hazard);
- human vibration tolerance is modified by simultaneous, sustained acceleration exposure.

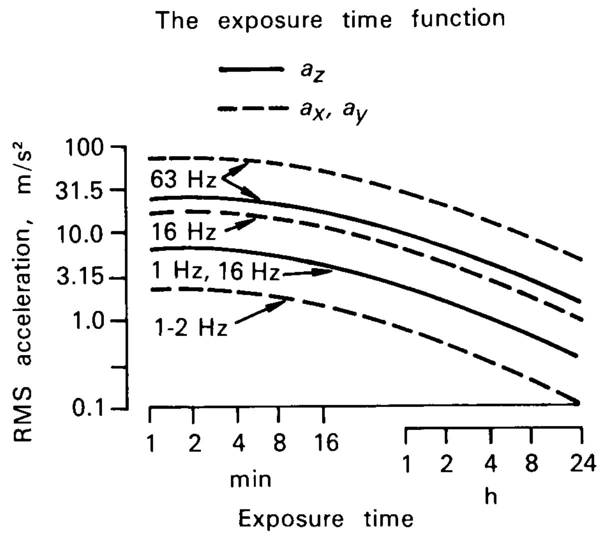

FIGURE 25.—Proposed ISO "Fatigue-decreased proficiency" boundaries (the time function) [61].

The first two of these factors have been studied in specific tests under realistic conditions (Fig. 26). Such tests clearly show that the supine couch position is less favorable in regard to human vibration tolerance than the upright sitting position.

The reason is that the direct transmission of vibratory energy from the couch to the astronaut's head in the supine position results in head symptoms limiting physiologic and subjective tolerance and leads to performance decrements at relatively low-vibration magnitudes [25, 122, 128, 129]. In the supine position, the vibration transmitted to the head is not attenuated by the intervening body structure as it is in the upright position. Depending on the helmet design and degree of restraint [38, 128], vibration of the helmeted head can affect tolerance as well as speech and visual capability.

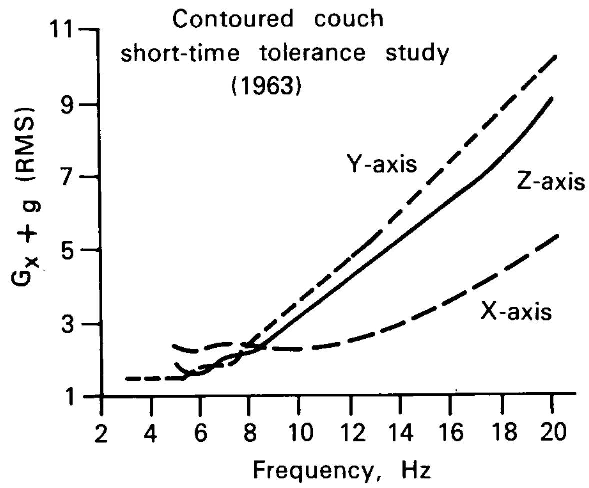

FIGURE 26.—Acceleration tolerance in three directions of vibration in a contoured couch [129].

Exposure limits for space operations have been generally accepted as the tolerance limits for healthy young subjects undergoing the stress for the maximum vibration exposure time (a matter of minutes) for the particular mission. It is logical in space flight not to apply the additional safety factor of 2 (or 6 dB) which was incorporated in the ISO Exposure Limits [61]. Those limits were intended to cover safely the case of repeated vibration exposure of general populations. (The same consideration can usually be applied to military or other occasional or nonroutine vibration exposures.)

The influence of sustained acceleration upon vibration tolerance is of considerable interest. In space operations severe vibrations almost always occur simultaneously with high acceleration loads. Based on limited experimental data and theoretical considerations, vibration stress and sustained acceleration stress do not appear to be synergistic [42, 45, 99]. Thus, the safety and performance limits established separately for each of these stressors could be safely adopted. The experimental evidence has shown that typical space rocket vibration (11 Hz at $\pm 3\ G_x$) in combination with moderate sustained acceleration (3.8 G_x) results in slightly increased vibration tolerance [25]. This paradoxical finding can be explained by the "restraining" effect of the sustained acceleration (with decreased transmissibility of low-frequency vibration to the body) which provides some protection (Fig. 21).

Principles of Protecting Man Against Vibration

In the classical approach to vibration control in engineering, four essential steps are taken:

1. Measure or predict the adverse environment.
2. Select and apply an appropriate criterion of control and a corresponding limit of exposure.
3. Determine the kind and amount of vibration control (usually reduction) required.
4. Select and apply the most economical and effective means of control.

These principles can be applied to protect man from aerospace vibration as well as to control vibration affecting engineering structures and equipment. Again, adopting the classical engineering approach in step 4, three main points can be distinguished at which to attack vibration disturbing to man:

at the source,
in the transmission pathway between source and man,
at the receiving point, i.e., in man himself.

Vibration Control at Source

The reduction of inputs from external sources remains largely a theoretical option in space operations.

Reduction of vibration from internal sources in space vehicles. There is scope for improvement (preferably at the design stage rather than by retrospective treatment of troublesome sources of spacecraft vibration) in the engineering of secondary sources of troublesome vibration and noise in spacecraft equipment.

Longitudinal ("pogo-stick") vibration of space boosters excited by the main propulsion units had to be reduced substantially (at considerable expense) during the development of the launching vehicles used in the US manned spaceflight program. The requirement for reducing vibration levels in those vehicles was dictated by both equipment and human tolerance limits.

Control of Vibration in Transmission from Source to Man

Minimizing the response of structures. Vibration disturbing to the astronaut can be reduced by preventing structural resonances in the vehicle and its internal equipment wherever possible. This can be achieved frequently by the use of high-damping materials in the construction of equipment and vehicle components and, where it proves to be practicable, by damping treatments.

Isolation. Among the various ways of isolating man from vehicle vibrations, an important one is the interposition of springing or some resilient element between the man and the source of vibration [50]. There are rather strict limitations to the results that can be achieved by this device when the man is necessarily coupled closely to the vehicle structure, e.g., when the astronaut is restrained in his couch during launch. Perfect isolation is achieved, of course, when the astronaut floats freely in the weightless state. Attention should be given to possible sources of flanking transmission of vibration (e.g., stiff or rigid personal equipment connectors).

Minimizing Adverse Effects of Vibration Reaching Man

Where it is operationally feasible to minimize exposure to vibration, it is always worth considering the extent to which the duration or frequency of human exposure to vibration can be reduced. The opportunities for practicing this principle in space flight are limited.

Ergonomics of crewplaces and of displays and controls. Flight instruments and other equipment to be used in spacecraft during phases of the mission when there is severe vibration should be designed specifically for use in that condition. The legibility of flight instruments is one area where this principle may be applied [50]; another is the design and placement of manual controls such as console switches and control sticks. Tolerance of vibration and disturbing oscillatory motion in general is improved also when crewplaces are well-designed, comfortable, and pleasantly conditioned.

Training and experience. Individuals who must live and work in vibration and other abnormal states of motion (including weightlessness) show considerable and continuing habituation to the stress; with experience, they develop specific skills enabling them to carry out tasks in spite of the disturbance. Experience in both US and Soviet manned spaceflight programs has proved the importance of training and meticulous rehearsal of all phases of a space mission to the greatest extent possible in Earth-bound simulation, including simulation of vehicle vibration in phases where that condition is important in the spacecraft environment.

Physical fitness and freedom from undue fatigue are clearly of importance to the astronaut in all respects, including his tolerance of vibration and unusual motion. With the exception of remedies for motion sickness (see Volume II, Part 2, Chapter 4), no pharmacologic agents are known to increase human tolerance of vibration.

Summary

The vibration environments associated with space propulsion units and space maneuvers were carefully researched at an early stage in the development of manned space flight; it was not expected that vibrations would pose a major problem in space operations. Available guidance in regard to human safety and performance limits allowed dictating proper engineering specifications to forestall serious adverse effects upon the astronauts. Through careful research and testing of human and equipment capabilities in simulated space environments and mission, vibration has not been a seriously stressful factor in any USSR or US manned space missions carried out so far.

Human vibration research has added significantly to our understanding of the effects of biodynamic environments in general upon aerospace crews. This is particularly effective with regard to human protection against mechanical shock or impact, the field in which human vibration research has proved an indispensable key to the understanding and mathematical description of all manner of force and pressure environments. Research begun initially to support space programs has enhanced the development of biodynamics as a distinct discipline, which is contributing not only to aerospace medicine but also to occupational and general medicine and physiology.

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