9. SOUND AND NOISE

Prepared by

E. M. Roth, M. D., Lovelace Foundation
A. N. Chambers, Bellcomm, Inc.

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9. SOUND AND NOISE

Sound and noise problems arise at several points in space operations. Sound energy generated by boosters on the launch pad affects the crew on board the vehicle as well as ground personnel. Sound is also a critical factor in the design of communication systems. Excessive exposure to noise in the many facets of space operations can lead to temporary or permanent damage to the ear and interfere indirectly with the performance of critical tasks. The only novelty to the acoustic environment in space operations is limited to the role of high-energy, low-frequency (under 50 Hz) sound. Noise problems of the space age will probably be much more serious for ground support personnel than for the astronauts.

NOMENCLATURE AND UNITS

Sound is generally used to refer to any vibration or passage of zones of compression and rarefaction through the air or any other physical medium which is sufficient to stimulate the receptors of the ear or other body tissue.

Hearing refers to the response of the auditory system to sound. In order to be heard, these fluctuations must be of sufficient intensity to stimulate the cochlear receptors and they must also fall within, or contain frequency components within the spectral range of human hearing. This is commonly referred to as the audio-frequency range and may be considered to extend from about 16 to 20,000 Hz. Pressure oscillations at frequencies above this range are called ultrasonics. They cannot be heard by man but may nevertheless exert biological effects and are discussed briefly later in this section. At frequencies below 16 Hz such pressure oscillations can also exert biological effects and are, therefore, legitimately considered under the heading of "noise."

Signal is any pure tone or narrow frequency band that is used to convey information.

Speech refers to the human capability for generating meaningful sounds.

Noise refers to any undesirable sound or sound which does not convey information and can be produced by a single tone, a narrow frequency band, or a wide frequency band. All can vary in amplitude. The presence of noise with a signal tends to raise the minimum audible intensity of signal or speech above that in quiet surroundings. The phenomenon is called masking.

The basic dimensions or parameters of sound and hearing concerned with the pure tones are intensity (or amplitude), frequency, and duration as expressed in physical terms; and loudness, pitch, and duration as expressed in psychological (or subjective) terms. Other physical dimensions such as wave-form, etc., are mixtures of the basic dimensions of intensity and frequency. The existence of these two sets of measures indicates the lack of linearity between sound and hearing. Table 9-1 summarizes these terms and units.

Table 9-1

Terms and Units Used in Audition

Physical		Psychological	
Term	Unit/Measure	Term	Unit/Measure
Frequency	Cycles per second or Hertz	Pitch	Mel
Amplitude	Decibel $L=20\log(p_1/p_2)$	Loudness	Phon Sone
Duration	Seconds/Minutes	Duration	Seconds/Minutes

The unit used to measure intensity, L, in physical units is the decibel (dB) and is expressed as:

$$L = 20 \log (p_1/p_o) \qquad (1)$$

where p_1 = the sound pressure level (SPL) to be measured;
p_o = a reference pressure, usually 0.0002 μ bars or dyne/cm^2.

The difference between two sound pressure levels is expressed as:

$$L_2 - L_1 = 20 \log (p_2/p_1) \qquad (2)$$

The speed of passage of the zones of compression or rarefaction represents the velocity of sound, which is characteristic of the medium of propagation in given conditions. The separation of corresponding points in successive zones is the wavelength, which is inversely proportional to the frequency, according to the relationship:

$$\text{Wavelength } (\tau) = \frac{\text{Velocity of Sound (V)}}{\text{Frequency } (\eta)} \qquad (3)$$

For example, taking the velocity of sound in air at 0°C to be 1087 ft/sec, a 100 Hz tone will generate a disturbance with a wavelength of 10.87 ft.

The measure of frequency is simply cycles per second or Hz. A range of frequency may be indicated by the octave, which is the interval between any two frequencies having a ratio of 2 to 1. The duration is expressed in seconds or minutes.

The psychological measures of loudness are the phon and sone. The phon is merely a transformation of the sone into a logarithmic scale related in specific ways to the sound pressure level of a reference sound. Sounds that have equal sone value or phon value or presumed to be equally loud, and discriminations between the loudness of sounds can be reported in either sones or phones (see Figure 9-6). The mel is used as a subjective measure of differences in frequency between sounds. The psychological measures will be covered below.

The performance capabilities of the human ear for the reception of tones that are of primary concern here are the various thresholds for absolute and difference discrimination of intensity and frequency levels, both in quiet surroundings and with noise, as well as certain other complex discriminations. The thresholds include: (1) the absolute threshold which is the intensity at which a sound can just be discriminated from silence, (2) the difference thresholds which are the minimal differences (i. e., just noticeable differences) in intensity or frequency between signals that can be discriminated by the listener, and (3) the discomfort and damage thresholds which are the levels of intensity which, if of sufficient duration, will cause discomfort to the listener and, for higher levels, may cause pain and temporary or permanent reduction in hearing capability. The other capabilities for discrimination of sound are the localization of sound, both monaurally and binaurally, and the number of intensities or frequencies or combinations that can be discriminated both on an absolute or on a comparative basis. These capabilities are not of particular interest in space operations.

The representation of speech can be expressed as a function of time only (i. e., waveform), or as a function of frequency only (i. e., spectrum),or as a function of both time and frequency (i. e., intensity-frequency-time pattern). The capabilities of the human ear for the reception of speech of interest here have to do primarily with its intelligibility. The Articulation Index (AI) is the measure that ordinarily is used to compute the intelligibility of speech. The AI is defined as a weighted fraction representing, for a given speech channel and noise condition, the effective proportion of the normal speech signal which is available to the listener for conveying speech intelligibility (121).

Several general reviews of sound, noise, and audition are available (12, 13, 35, 65, 66, 82, 85, 155, 165). Standards for the physical measurement of sound are published (3).

SOUND PERCEPTION AND SPACE OPERATIONS

The human auditory system shown schematically in Figure 9-2 is adapted to respond to changes of air pressure at frequencies that range from about 16 to 20,000 Hz (upper limits are more variable than lower) and at root mean square pressures from about 10^{-4} to 10^{3} dynes/cm^{2}. The pressure changes move the tympanic membrane (ear drum), and this motion is modulated and transmitted through the "middle ear" by the lever action of three small bones, the auditory ossicles. The motion is transmitted to the cochlea (inner ear) as mechanical vibration and displacements of a membrane (the basilar membrane). The displacements generate electrical effects in sensory cells on the membrane which, in turn, generate patterns of nerve impulses in the neural parts of the auditory system. This is the physical basis for hearing. Signal processing characteristics of the peripheral auditory system are under study (76).

Figure 9-2

Anatomy of the Auditory Mechanism

(After Jerison(104), drawing of ear adapted from Gardner(63)(original by Max Brodel); upper diagram redrawn from Morgan et al (eds.)(66))

a. SCHEMATIC OF THE EAR

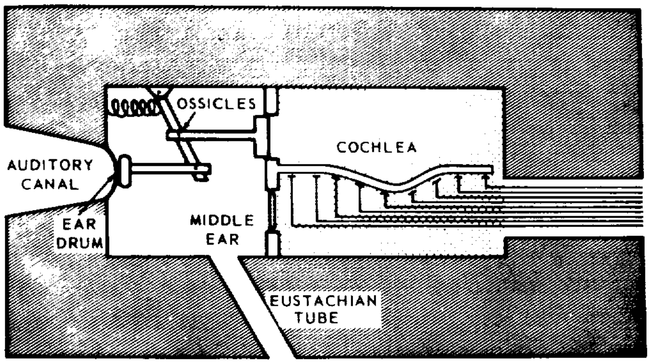


Figure a is a mechanical schematic of the major parts of the ear, showing the conversion of sound pressure waves into nerve impulses to the brain. The auditory canal acts as a resonating chamber, amplifying sound frequncies between about 2000 Hz and 5000 Hz by from 5 to 10 dB. The peak human sensitivity to such tones, as shown in Fig. 9-9a (bottom curve) is due to this amplification.

b. CROSS-SECTION OF THE EAR

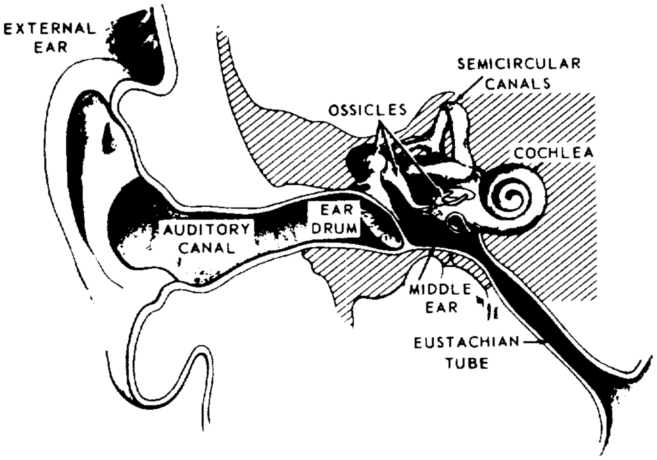
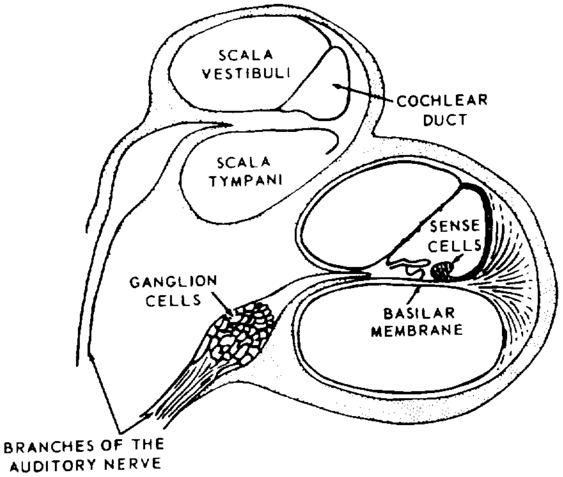


Figure b is a simplified drawing of the ear. The eardrum is a tough thin membrane that transmits pressure changes from the external ear to the middle ear bones or ossicles. The ossicles - the malleus (hammer), incus (anvil), and stapes (stirrup), weighing together about 50 mg - are the smallest bones in the human body. They transmit and transform the vibrations of the 75 mm^2 eardrum into vibrations of the 3 mm^2 oval window. The oval window is at one end of the internal ear or cochlea, a snail-shaped tube. Sound waves reaching the oval window by the motion of the stapes produce complex wave motions in an incompressible fluid in the cochlea.

c. CROSS-SECTION OF THE COCHLEA



The cochlea is presented in magnified section in Figure c, which shows the four large chambers filled with the fluid which carries the vibrations to the sense cells. These sense cells, about 30,000 in all, can transmit this information as patterns of excitation in the auditory nerve, and eventually as patterns of excitation in the brain.

At another level of analysis, the neural response to patterns of pressure changes may be considered as a "message" that is encoded, decoded, fed back o the sense cell, and transformed into other messages to the machinery of he body. The complete analysis of this response requires the tools of elecrophysiology and experimental psychology. At very basic points in the neural network one discovers complex interactions; for example, the sensitivity of he sense cell, which might appear to depend only on its physical properties, urns out to depend also on whether or not the observer is paying attention.

The analysis of hearing can also be accomplished by treating the human observer as a black box to be analyzed in input-output terms. This is the psychophysical approach of experimental psychology. It is concerned with the relationship between an observer's behavior (including his reports about his experience) and the physically defined stimulus.

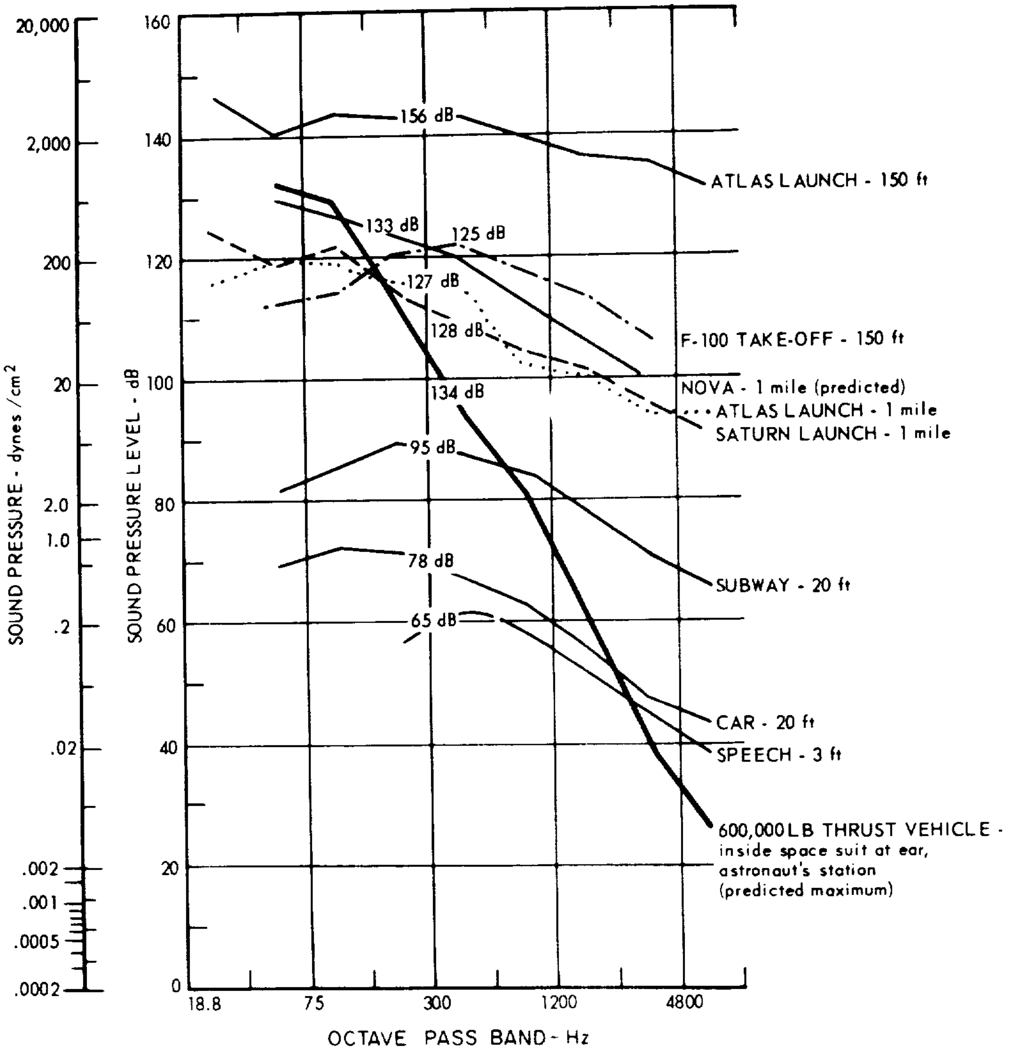
During space missions the major concerns will be to protect the auditory system from damage from excessive sound, and to provide an environment that will permit auditory communications. For these purposes the most important facts come from the "black box" approach. Data from this approach will be emphasized here, but some results of other levels of analysis of the auditory system will also be presented.

In order to facilitate evaluation of the acoustic environments in the space program, an electronic dummy or manikin which represents the average male torso from the xiphoid process upward is under development (26). Providing an exact replica of the human head, including the simulation of natural flesh impedances, the dummy features an artificial voice which produces levels up to 100 dB SPL at six inches, and a highly advanced artificial ear which measures sound pressures at the eardrum or the entrance to the ear canal. A unique hearing-mode amplifier optionally provides automatic and continuously variable loudness-contour equalization.

The Acoustic Environment

Sounds of the sort that will be and have been encountered in aerospace operations, as well as some everyday sounds, are described in Figure 9-3. The rocket noise levels in this figure were from early prediction studies and should not be used in any calculations (vide infra).

The external sound field of a space vehicle during the launch is filled principally by the jet noise of the booster rockets (32 , 69 , 81). Prediction of near field noise has received analytic study (150). Because of the directivity of the jet noise, the zone of maximum sound intensity produced on the ground is in the form of a ring which spreads outwards from the launching pad as the vehicle ascends in a vertical launch. Once it is well clear of the ground, the rocket emits noise as a practically spherical radiation. The noise grows fainter and changes to a muted, low-frequency rumble heard from below as the rocket gains altitude. The sound attenuation and fall in pitch with increasing distance are augmented by the rarefaction of the atmosphere and the gathering speed of the vehicle, the noise of which often appears to a listener on the ground to disappear abruptly. As the vehicle accelerates off the pad, noise



This graph shows physical descriptions of some common and uncommon sounds. Measurements with commercial sound level meters and octave band analyzers give sound pressure level (SPL) in decibels (dB) relative to the reference level, and the ordinate can serve as a nomogram for converting from one measure to the other. (The conversion is logarithmic). Overall sound pressure level of each curve is shown numerically on the curve. The source of each curve and the distance between the point of measurement and the noise source are indicated at the right. Major difefrences between rocket noises from either Atlas, Saturn, or (predicted) Nova and other sources are in the very high energies of the rockets at frequencies below 75 Hz. The very unusual spectrum of noise predicted for the Mercury astronauts was based on the sound shielding properties of the capsule, space suit, helmet, and earphones of the Mercury configuration. These attenuate higher frequency sound more effectively than lower frequency sound.

Figure 9-3

Rocket Noise and Everyday Sounds

(After Jerison(104), from the data of Cole et al(33), Hoeft and Leech(97), Cole et al(31), Clark(28), Bonvallet(14), and French and Steinberg(59)) from this source extends far into the surrounding community but quickly diminishes within the crew compartment. With increasing airspeed, however, the crew compartment receives aerodynamic noise generated by boundary layer turbulence. This boundary layer noise reaches its maximum level as the vehicle passes through the range of maximum dynamic pressure (max q) and progressively decreases thereafter. It becomes insignificant as a noise source within approximately two minutes after lift-off. Aerodynamic noise also increases in level and peaks at lower frequency as vehicles are larger. For capsules in the size range of Apollo and greater, noise at maximum dynamic pressure will peak below 100 Hz (see Figure 9-4).

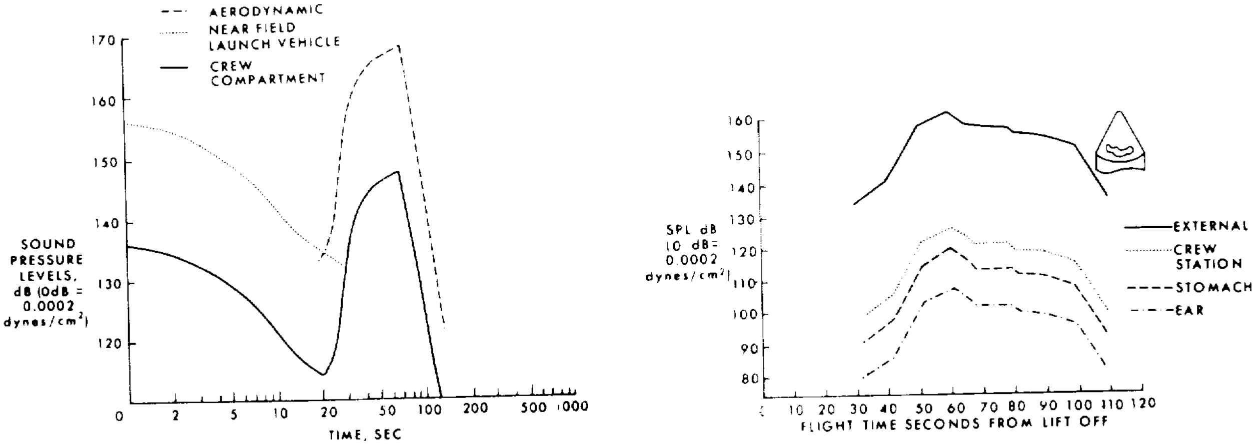
The acoustic environments generated by aerospace systems in being and under development are or will be, more severe in the low frequency range than any previously encountered (138, 150). Because there are no large rotating or reciprocating parts in a rocket engine, the noise of rocket vehicles does not normally contain discrete frequency components. However, structural resonances excited by distributed noise and transients, or by auxiliary sources such as pumps in liquid-fueled machines, can contribute to the internal sound field of rocket-propelled vehicles. The level of very low frequency noise (1-100 Hz) produced by the turbulent mixing of the booster propulsive flow with the surrounding atmosphere generally rises as the booster increases in size and thrust. It has been estimated that the very large super boosters of the future (e. g., Nova) will produce their maximum noise energy in the infrasonic range (below 20 Hz) (143). Occasionally, a periodicity can develop in primary rocket engine noise, due to unstable conditions. The directivity of rocket noise in the far field is less marked than that of turbojet engine noise, although a similar postero-lateral directivity maximum does occur.

Figure 9-4a presents a predicted (by calculation) time-history of external and crew compartment noise during a typical spacecraft launch for a system of the Apollo size (57, 106, 141, 142, 148, 149). Figure 9-4b shows the actual overall sound-pressure levels measured during the launch. The topmost curve is the external noise that has been measured on the command-module shoulder. These data were collected during Apollo boilerplate development missions and are scaled to a nominal Saturn launch-vehicle trajectory (57, 141, 142). As predicted from wind-tunnel data, the noise became significant approximately 20 seconds after lift-off, and increased to a sound pressure level of 162 decibels (106, 149). The noise remained intense throughout the high dynamic pressure region and became insignificant 100 seconds after lift-off. The curve labeled "crew station" shows the overall time-history of sound pressures expected in the crew compartment. These data were calculated by subtracting the overall noise reduction that had been measured during a command-module ground test from the external noise levels. Since the crewmen will be wearing space suits during launch, the noise reduction measured for the helmet (see Figure 9-52) and space suit was subtracted from the crew-station noise levels. The curves labeled "stomach" and "ear" represent an estimate on the crewmen's environment during launch. These data clearly demonstrate that a crewman will be exposed to overall sound-pressure levels of 95 decibels or more for about 60 seconds. For the trajectory considered, the maximum sound-pressure level will occur 60 seconds after lift-off.

Figure 9-4

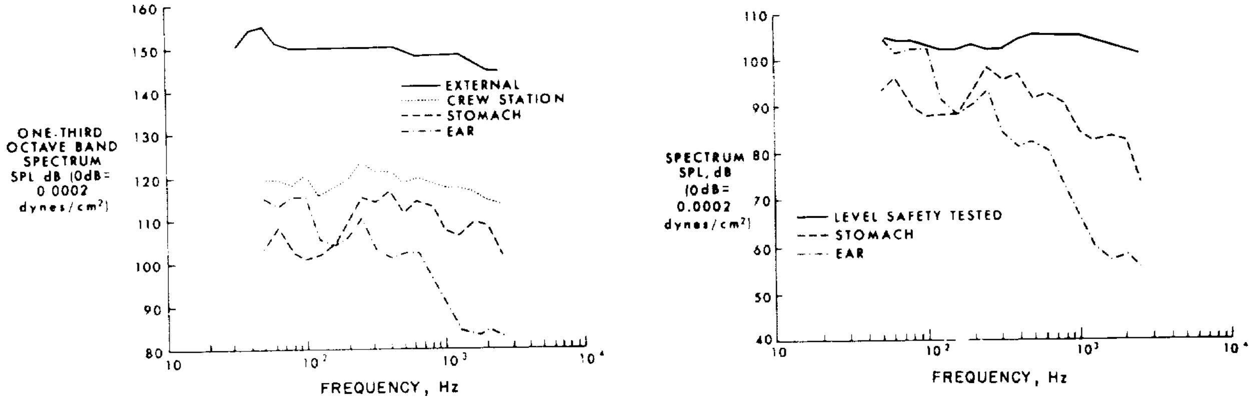
Predicted Sound Pressure Environment Inside and Outside
Apollo Spacecraft at Launch (See text)

(After French(57))



a. Predicted Overall Time History of External and Crew Compartment Noise (Calculated)

b. Overall Sound-Pressure-Level Time Histories for Apollo Mission (Measured)



c. One-Third Octave-Band Frequency Spectra for Apollo Mission at T + 60 Seconds (Measured)

d. Spectrum Sound Pressure Levels for Apollo Mission at T + 60 Seconds (Measured)

Figure 9-4c presents a one-third octave-band frequency analysis for this flight time. The curves are labeled to correspond with the overall levels shown in Figure 9-4b. The external noise levels were recorded in flight, reduced to one-third octave-band levels, and corrected to a nominal trajectory. The crew-station noise levels were calculated by subtracting the noise reduction of the command module at each one-third octave-band from the external noise levels. The spectra for the stomach and ear were obtained by subtracting the one-third octave-band noise reduction measured for the suit and helmet from the crew-station levels. These data show that the external noise spectrum is flat with a maximum of 155 decibels around 50 Hz. After the noise has been transmitted through the spacecraft, the spectrum is still reasonably flat, but the maximum sound-pressure level of 123 decibels occurs at 250 Hz. The spectrum on the stomach has the highest sound-pressure levels in the 250 to 800 Hz range, and the maximum of 116 decibels occurs at 400 Hz. The spectrum at the ear is unique in that the maximum noise level of 115 decibels occurs at 50 Hz and the sound-pressure level decreases as the frequency increases. It is also important to notice that the overall sound sound-pressure level calculated by using the measured overall noise reduction. The difference is due to the dynamic response of the helmet at frequencies below 200 Hz (see Figure 9-52).

The one-third octave-band spectra at the stomach and ear, shown in Figure 9-4c were converted to spectrum levels or sound-pressure level per cycle and presented in Figure 9-4d. The curve marked "level safely tested" is the sound-pressure level per cycle tested during the program where adverse physiological effects and performance decrements were not reported for a 1-minute exposure. (See below under discussion of Figure 9-36).

During reentry of a capsule, boundary-layer turbulence again generates an internal sound field containing broadband noise of high intensity (69). The sound pressure levels reached are comparable with those produced during the maximum dynamic pressure period at launch but high intensities may be maintained for longer periods during reentry. Current,overall,ambient noise level for the Apollo spacecraft is estimated at 87 dB. This level is relatively consistent throughout all phases of the mission with the exception of the launch phase.

During captive firing of rocket engines in ground installations, continuous broadband noise is emitted for as long as the test is continued. The spatial distribution of this noise in the surrounding field depends upon the factors affecting the propagation of sound through the air and the directivity of the source. Exhaust blast deflectors and diffusers are commonly used in captive firing installations and can modify considerably the basic directivity (30, 151). A proportion of the noise from ground firing can be propagated for considerable distances as ground-borne vibration, which can be disturbing both mechanically and as the source of re-radiated acoustic noise.

Figure 9-5 represents a summary of the frequency environments experienced in operational situations as well as in test facilities for low frequency noise.

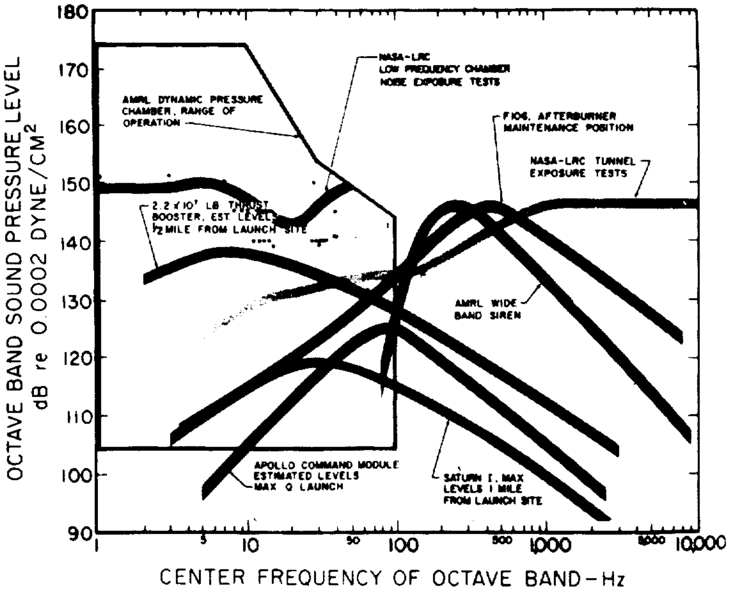


Figure 9-5

Low Frequency Noise Experiments Used in Human Exposure Tests

In a series of tests, a limited number of healthy human subjects safely tolerated, without gross performance decrements, the sound spectra indicated. The dots indicate the individual exposures to the NASA-Langley Research Center Low-Frequency Chamber. The measured spectrum for a Saturn booster and the estimated spectrum for a 2.2 x 10^7 lb thrust booster are to indicate the shift of the noise spectrum to lower frequencies with increasing thrust.

(After von Gierke(68), adapted from Mohr et al (138))

Factors affecting the propagation of sound in air have been studied (28, 82, 84, 169, 170). Theoretically, the spherical radiation of sound waves from a point source obeys an inverse square law of intensity, so that the sound pressure amplitude is inversely proportional to distance from the source. In other words, the SPL drops by 6 dB for each doubling of distance (the divergence decrease). An additional attenuation of sound in air is brought about by molecular damping processes, the effect of which is strongest at high frequencies. In practice, the pattern of propagation of sound is further complicated by atmospheric inhomogeneity and movement, as well as by obstacles in the sound field.

The attenuation of sound in air takes place through energy-dissipative processes (viscous, thermal and relaxational) occurring both within and between the molecules of the medium. An important part of the acoustical damping in air is due to a relaxation effect between the vibrational states of the oxygen molecule. This effect is strongly enhanced by the presence of water molecules, with the result that sound attenuation in the atmosphere is increased when the humidity is high (84). Fine particulate moisture (fog, drizzle, light snow) produces a negligible attenuation, however, and indeed a paradoxical increase in noise propagation can be observed in these conditions. This is attributable to other factors, present at the same time, which encourage the propagation of sound, such as thermal homogeneity and the absence of wind.

The velocity of sound, c, depends upon the air temperature, according to the formula:

$$c = c_o(T/T_o)^{1/2} \qquad (4)$$

in which T is the absolute temperature of the air under consideration. Because the air temperature normally decreases with altitude, sound radiated from a source near the ground is refracted upwards. A temperature inversion produces the opposite effect and can give rise to a paradoxical increase in noise with increased distance from the source.

When a wind is blowing, the pattern of sound propagation is distorted. A sound shadow is created upwind from the sources. In moderate wind, SPL differences of as much as 30 dB can be measured between upwind and downwind positions at the same distance from the source of sound. Sound is also reflected and diffracted by obstacles in the sound field (169). The scattering of sound by buildings, hillocks, and other surface features reduced the overall propagation of noise into the far field. Roughness of the ground and vegetation also produce losses by the absorption and scattering of sound waves passing over the terrain (208). Considerable losses by scattering can result from meteorological turbulence (99).

Data are available on levels, spectra, and acceptability of noise from ground vehicles (14, 24, 152). It is clear from the above discussion that most of the inflight problems associated with the ear and hearing will probably be concerned with the efficiency of the auditory system for communications work. The following discussion is intended to summarize present knowledge of the biological aspects of auditory communication.

Absolute Threshold for Intensity and Frequency

The auditory response to the frequency of pure tones is commonly accepted as falling between about 16 and 20,000 Hz as indicated in Figure 9-6.

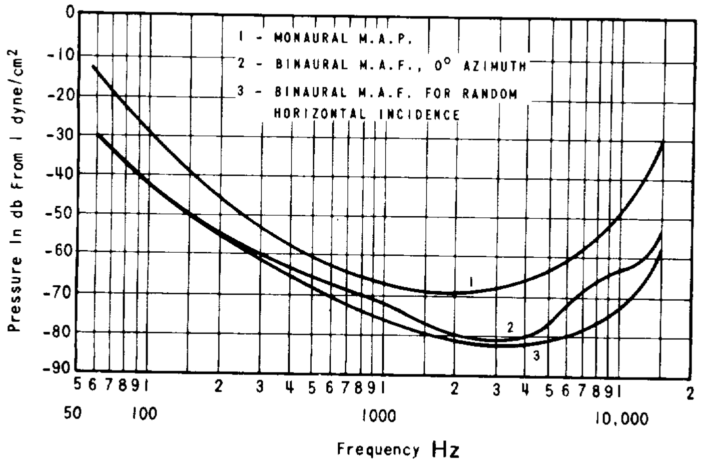


Figure 9-6

Absolute Thresholds for Reception of Signals

M.A.P. stands for "Minimum Audible Pressure".

M.A.F. stands for "Minimum Audible Field".

(After Sivian and White (175))

The limits for response to intensity vary as a function of frequency. They are often different for different individuals and the threshold may vary from time to time in the same individual (86). The limits for response to intensity extend from the minimum level (i.e., absolute threshold) at which a sound can be heard to intensities where feeling and discomfort begin. The minimum intensities to which the ear will respond vary as much as 80 dB with the greatest sensitivity between 2000 and 4000 Hz. Individual differences in absolute thresholds vary as much as 20 dB and can vary as much as 5 dB within a short period of time.

The audibility of a signal depends on the duration since the response of the ear is not instantaneous. For pure tones, about 200-300 msec. are required for buildup and approximately 140 msec. to decay. Thus, tones of less than 200-500 msec. do not sound as loud and are not as audible in noise background as sounds of longer duration.

Difference Thresholds for Intensity and Frequency

Detectability of just-noticeable-differences (JND'S) in intensity is dependent on both intensity and frequency (87). At sensation levels of 20 decibels or less, the intensity increment that is just noticeable as a loudness change is comparatively large, being on the order of 2 to 6 decibels, depending on the frequency. Above a sensation level of about 20 decibels an intensity increment of about 1/2 to 1 decibel is detectable, except at the frequency extremes, where the increment is somewhat larger. Within the frequency limits of about 500 to 1,000 Hz, just-noticeable-differences of intensity are smallest. The curves for difference thresholds are presented in Figure 9-7.

The frequency difference required to produce a just-noticeable-difference in pitch varies essentially according to frequency at low frequencies. Smaller differences in frequency are detected at high than at low frequencies. This just-noticeable-difference of pitch is not wholly dependent on frequency in that the sensation level is a contributing factor. Below a sensation level of 20 dB, the ear rapidly loses its ability to detect frequency changes; above this level, the ear will fairly consistently detect a change of 3 Hz in a tone of 1000 Hz or less. Beyond this frequency, the just-noticeable-difference remains fairly constant at 0. 3 of one percent of the tone's frequency.

The difference thresholds for frequency are presented in Figure 9-8. Carrying capacity of the auditory system for pure tones is such that about seven distinct pitches and seven distinct loudnesses, or about 49 pure tones all told, can be identified on an absolute basis. Figure 9-9 presents equal-loudness contours for pure tones (66, 104). Figure a is in a free field, and figure b is with headphones. The numbers on the curves are their loudness levels in phons. The phon -unit was developed to identify tones according to their loudness as perceived by people rather than their sound energy as sensed by instruments. It was determined by matching the loudness of each tone with a 1000 Hz tone. The loudness of the tone is defined as the same number of phons as the number of dB SPL (sound pressure level) of the 1000 Hz tone that matched it. The bottom curve in figure a is the pure tone threshold for hearing which varies with age (190).

As an example, an engineer is required to construct a two-tone signal of constant loudness. If the tones are 100 Hz and 500 Hz in a free field and the higher tone is set at 60 dB, this tone will have a loudness of about 64 phons. A 64-phon 100 Hz tone in a free field, according to figure a would have to be at an SPL of about 70 dB. The two tones should therefore be 70 and 60 dB, respectively, to be perceived as equally loud.

To compare tones at different loudnesses, it is necessary to state the relationships of the loudnesses, and this can be done with the sone-scale. Sones are related to phons logarithmically and the conversion can be accomplished with

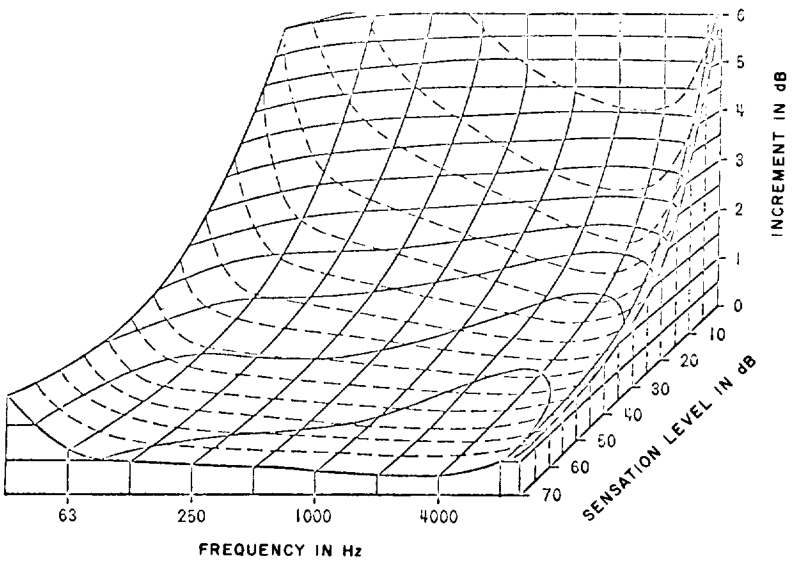


Figure 9-7

Difference Thresholds for Intensities of Signals

Three-dimensional surface showing the differential intensity thresholds as a function of the frequency and the intensity of the standard tone. The threshold is represented as the difference in decibels between the standard intensity and the standard plus the increment. Following the contour lines from 1000 Hz and 30 dB, one sees, by way of illustration, that the intensity of a 1000-Hz tone must be raised 1.0 dB from a level of 30 dB above threshold before the average observer can detect the change. If one starts with levels 60 or 70 dB above threshold, he finds that an increment of less than 0.5 dB is detectable.

(After Stevens(183), from the data of Riesz (161))

Figure 9-8

Difference Thresholds for Frequency of Signals

Three-dimensional surface showing the differential frequency threshold as a function of the frequency and the intensity of the standard tone. Frequency discrimination is poor at intensity levels near the absolute threshold (rear part of figure) and at high frequencies (right-hand part of figure). At sensation levels above 30 dB and at frequencies below 1000 Hz, however, a change of about 3 Hz can be detected.

(After Stevens(183), from the data of Shower and Biddulph (176))

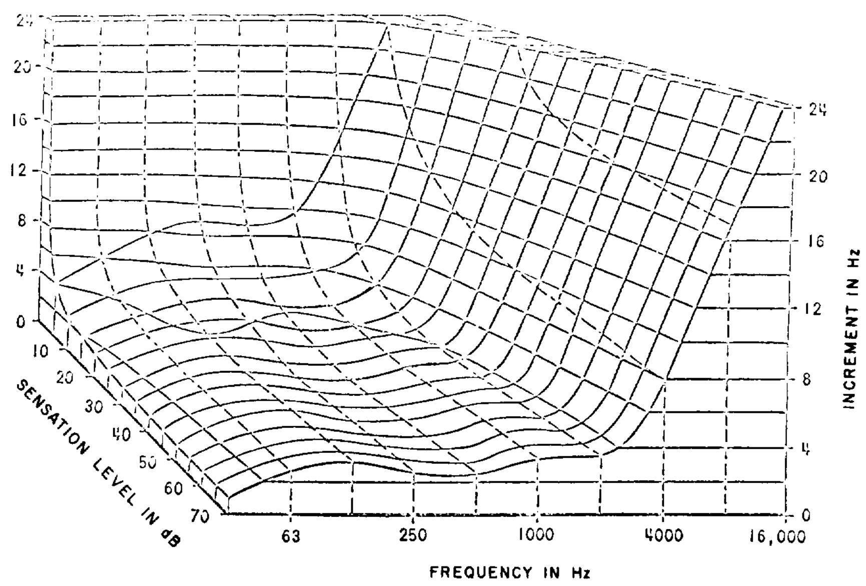
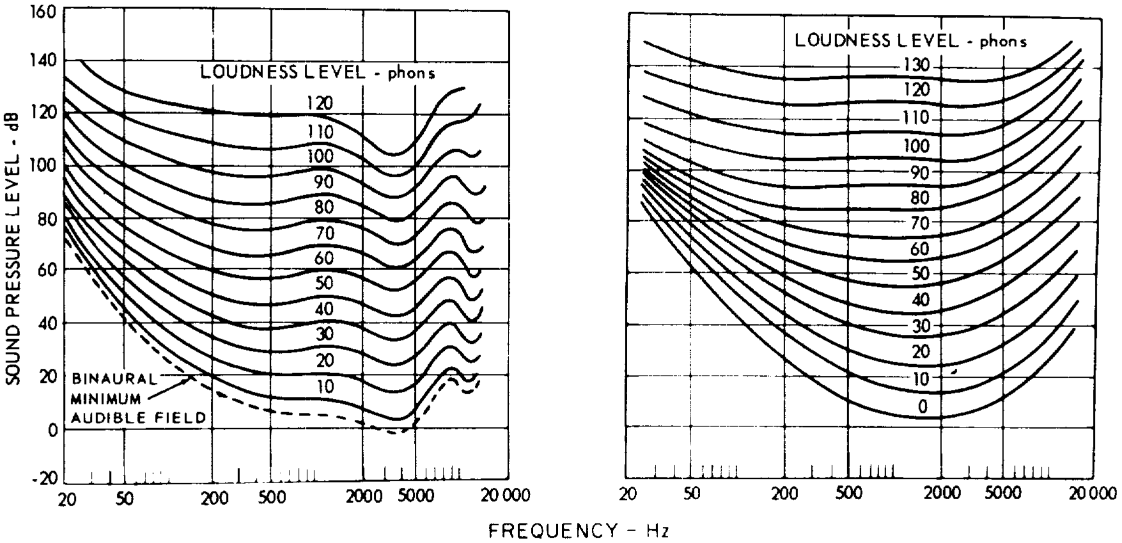


Figure 9-9

Sound Perception of Pure Tones

(After Gales et al(66))



a. Free Field **b.** Headphones

the nomogram in Figure 9-10a. By international agreement, 1 sone has been defined as the relative loudness of a sound whose equivalent loudness is 40 phons. In exponential form:

$$\text{Number of sones} = 2^{(p-40)/10} \qquad (5)$$

where p is the number of phons. The sone scale permits one to compare directly the intensities of experience. That is the purpose of this scale. The decibel equivalent or phon scale does not permit such a comparison. The resulting relationship between phons and sones is illustrated in Table 9-10b which also indicates some representative loudnesses of familiar noises.

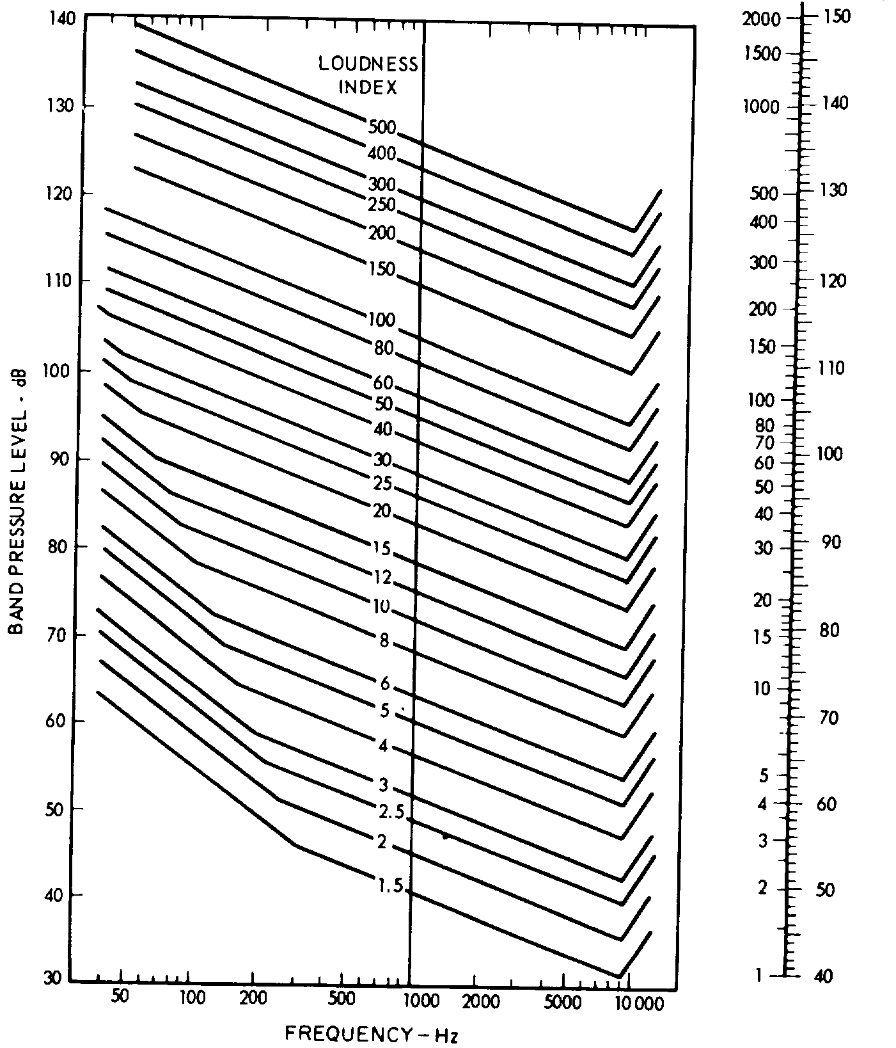
One can illustrate the use of the sone concept by the following. Example: To double the loudness of the tones in the preceding example, 64 phons first are converted to sones. The nomogram in Figure 9-10a shows that 64 phons = 5.2 sones. Twice the loudness would be equal to 10.4 sones. This in turn is seen from the nomogram to be 73 phons. From figure a. one can determine that the new signal would have the 100 Hz tone at about 80 dB and the 500 Hz tone at about 68 dB by finding the SPL's of tones at these frequencies that lie slightly above the 70-phon curve.

To illustrate the calculation of loudness with the chart and formula of Figure 9-10a, the data on sound pressure levels at an astronaut's ear and from a Century series fighter, as presented in Figure 9-3, are analyzed by the steps laid out in Table 9-10c. Octave bands are shown in column (1), and the geometric mean frequency of each band in column (2). Sound pressure level in decibels for each band, as estimated from Figure 9-3, is shown in column (3). The formula shown under Figure 9-6 for adding sones takes $F = 0.3$ because the data are in octave bands. The formula of Figure 9-10a is as follows:

Figure 9-10

Perception of Sound Loudness

a. The Sone and Phon Concept



$$S_t = S_m + F(\Sigma S - S_m)$$

This figure and the accompanying equation are used to estimate how loud a complex sound such as rocket noise will seem to an observer. To use the figure, one must have physical measures of the noise from a sound level meter and sound analyzer or one must be able to predict values for those measures. The figure gives the loudness index for bands of noise at the indicated geometric mean frequencies and band pressure level (total SPL for the band); for example, a band with a geometric mean at 200 Hz and SPL of 100 dB will have a loudness index of about 40. When the results of a particular sound analysis are available, the total loudness (subjective "intensity") of the sound can be calculated with the equation.

In the equation, S_t is the total loudness in sones, S_m is the highest loudness index measured, ΣS is the sum of the loudness indices for all of the bands of noise. The Factor, F, is 0.3 if the analysis is by octave bands, 0.2 for half-octave bands, and 0.15 for third-octave bands. The nomogram at the right of the figure permits conversion of sones to phons, which are related to the familiar decibel scale of sound pressure level.

(After Jerison(104), from Stevens(184))

Figure 9-10 (continued)

b. Representative Levels of Equivalent and Relative Loudness

Equivalent loudness (phons)*	Relative loudness (sones)	Example of noise at particular level	Facility of conversation
140	·	Large Rocket Engine at 100 yd	
		50 h.p. Victory Siren at 100 ft	
		Approximate Threshold of Aural Pain	
		Jet Engine at 50 ft	
130	—	Carrier Island during Jet Operations	
120	256	Close to Rivetter at Work	
		Boiler Shop, Weaving Shed	Impossible
		Near Orchestra in Loud Symphonic Finale	
110	128	Loud Motor Horn at 20 ft	
		Light Aircraft Engine at 50 ft	By shouting
100	64	Inside Propeller-driven Airliner	
		Inside Underground Train at Speed	
90	32	Busy Motor Traffic passing at 20 ft	
		Cocktail Party	
80	16	Moderately Loud TV or Radio playing Indoors	By raised voice
70	8	Normal Conversational Speech at 3 ft	Normal
		Inside Railway Sleeping Car	
60	4	Inside Quiet Saloon Motor-car	
50	2	Quiet Office or City Street at Night (Ambient)	
40	*1*	Average Level in Quiet Residence (Children Asleep)	By whispering
30	0·5	Broadcasting Studio (Ambient)	
		Quiet Whisper	
20	0·25	Quiet Countryside at Night (Ambient)	
10	--	Rustling Leaves	
0	-	Silence (Approximate Threshold of Hearing)	

* Numerically equal to dB re 0.0002 b at 1000 Hz only.

(After Guignard[82], Crown copyright)

c. Example of Band Analysis of Loudness Perception

(1)	(2)	(3)	(4)	(5)	(6)
		Mercury Astronaut's Ear (estimated)		Century Fighter 150 feet overhead	
Octave Band	Geometric mean frequency	Band Pressure	Loudness Index	Band Pressure	Loudness Index
37.5-75	53	133	300	113	70
75-150	106	130	300	115	100
150-300	212	113	120	120	180
300-600	425	95	37	123	275
600-1200	850	82	18	118	240
1200-2400	1700	60	5	113	200
2400-4800	3400	40	2	108	175
4800-9600	6800	26	0	---	---
ΣS (sum of loudness indices)			782		1240

(After Jerison[104])

For Astronaut: $S_t = 300 + [0.3\ (782-300)] = 445$ sones = 128 phons by nomogram 9-10a.

For Century Fighter: $S_t = 275 + [0.03\ (1240-275)] = 565$ sones = 131 phons by nomogram 9-10a.

Since 445 sones is about 80 percent of 565 sones, the apparent loudness of the Mercury rockets in the capsule at lift-off should be about 80 percent of the loudness in the cabin of a Century fighter flying overhead at 150 feet under full military power.

Pitch

Pitch, like loudness, is also a subjective attribute of sound. It is determined primarily by frequency, although it is affected somewhat by loudness, spectrum, etc. (123, 147). A scale for the quantitative rating of the magnitude of pitch in a manner similar to that described above for loudness has been established (66). The unit of this scale is the mel, which is defined as the pitch of a 1, 000 Hz pure tone at a level 40 dB above absolute threshold.

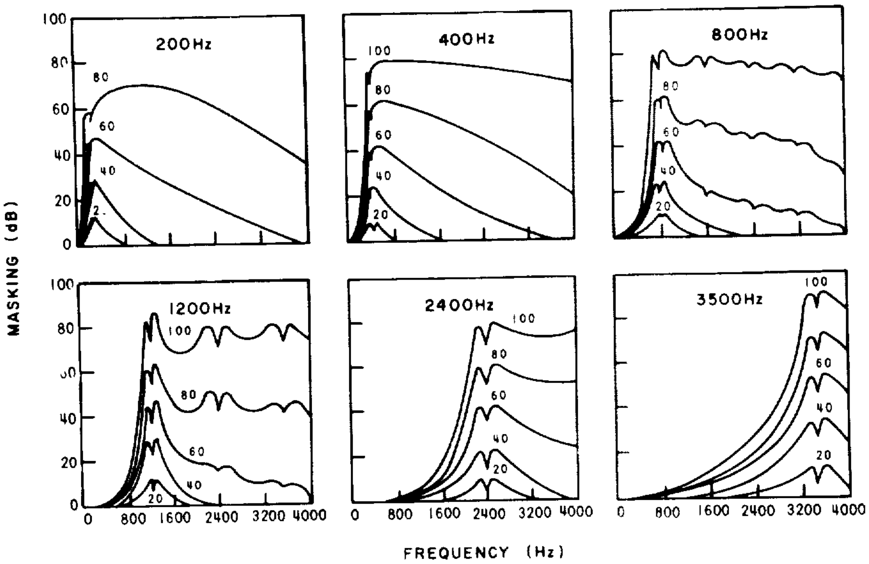
Masking of Sound Signals by Noise

Because few environments are free of noise, noise is usually a limiting factor in a signal-processing system. Design of a signal-processing system must separate signal from noise. Noise mixed with a signal tends to raise the threshold for hearing that signal above the threshold in quiet, or absolute threshold. This phenomenon is called masking, and the elevated threshold is known as the masked threshold.

Monaural (Pure Tone) Masking

The masking of a signal, basically a pure tone, by another pure tone must be determined experimentally. The masking thresholds of signals for various representative frequencies and amplitudes as they are affected by pure tones of various frequencies and amplitudes are depicted in Figure 9-11. These are based on monaural reception of signals and noise. It will be noted from these curves that the masking effect is greatest when the signal and noise are of similar frequencies and is greater for noise frequencies below the signal frequency than for noises above the signal frequency. At relatively high intensities, however, the masked threshold of signals that are some integral multiple of the masking tone is raised more than the threshold of those signals having no harmonic relationship to the masking tone.

In interaural masking (i. e., when the signal is fed into one ear and the noise into the other) no masking occurs when the noise SPL is relatively low (below 40 or 50 dB). When the noise SPL is above 50 dB, the sound is con-



Masking as a function of frequency for masking by pure tones of various frequencies and levels. Number at top of each graph is frequency of masking tone. Number on each curve is level above threshold of masking tone.

Figure 9-11

Masking of a Signal by Pure Tones

(After Wegel and Lane(206))

ducted through the bone of the skull to the opposite ear to produce masking as in the monaural case.

Masking by Narrow-Band Noise

The masking of a signal by narrow-band noise is similar to those for pure-tone masking except that the sharp dips caused by harmonics are absent. Figure 9-12 shows representative curves for monaural reception.

Masking by Wide-Band Noise

Figure 9-13 shows the masked thresholds for a pure tone masked by wide-band noise of uniform spectrum (i. e., white noise). The amount of masking of a signal by wide-band noise can be predicted if the spectrum level of the noise is known at the frequency of the signal tone. In making such a prediction it is assumed that the masking is caused by noise frequencies which lie in a band near that of the signal. When used to predict masking, this critical band-width is so defined that the SPL of the noise in the critical band is just equal to the SPL of the signal at its masked threshold. Figure 9-14 shows the generally accepted values of critical band-width as function of frequency.

The prediction of masking threshold at a given signal frequency (f) may be determined by measuring the spectrum level of the wide-band noise at the frequency of the signal. Correct this measured level to the level in the

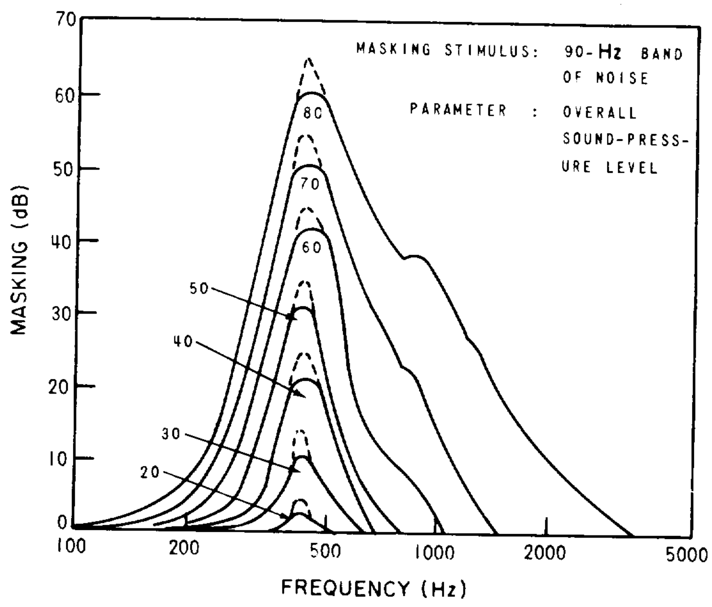
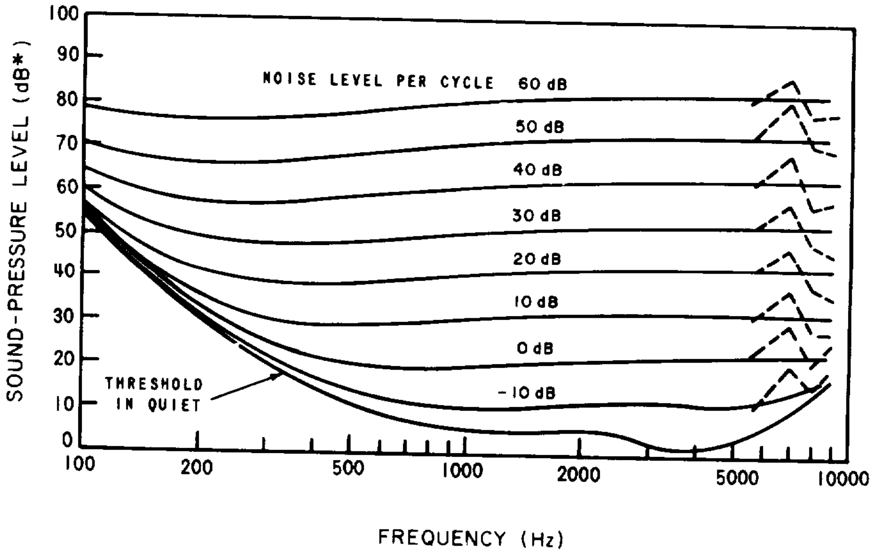


Figure 9-12

Masking of a Signal by Narrow-Band Noise

(After Egan and Hake[46])



* Re 0.0002 μ BAR

Figure 9-13

Masking of a Signal by Wide-Band Noise

(After Hawkins and Stevens (89))

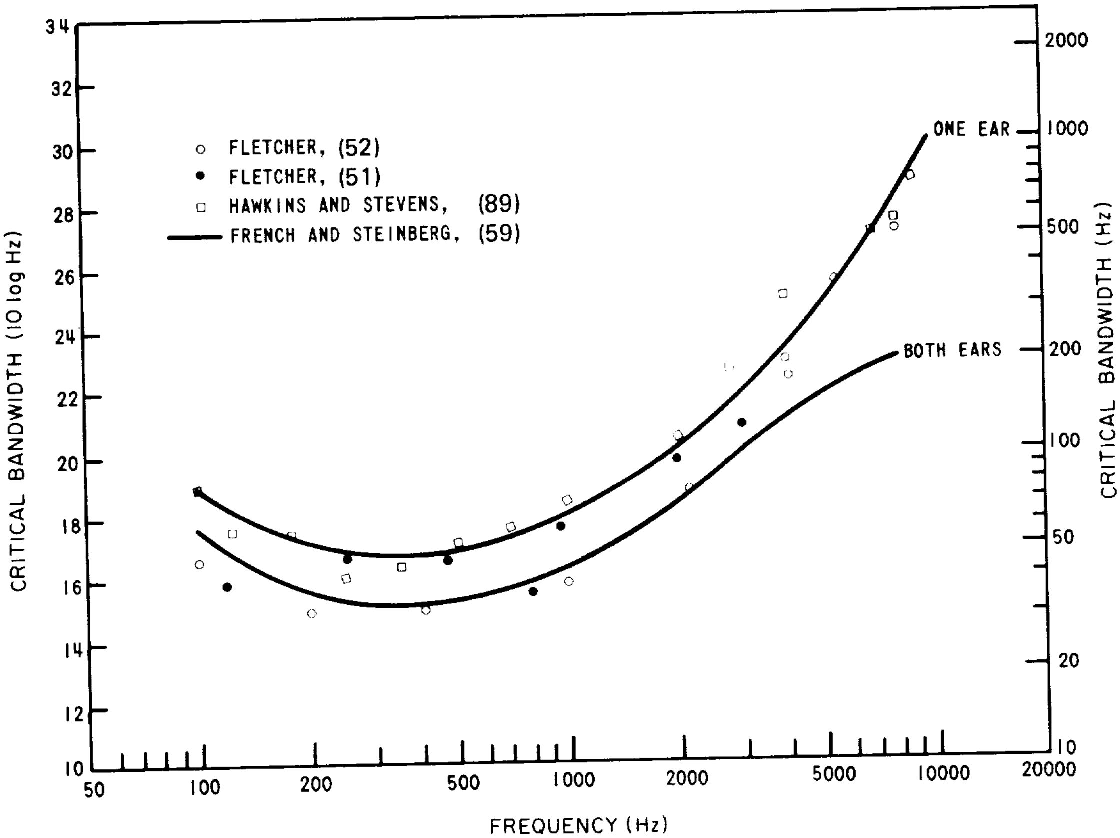


Figure 9-14

Critical Masking Bandwidth as a Function of Frequency

(After Gales et al[(66)])

critical band at f by adding the 10 log of the critical band-width. This correction can be read directly from the left-hand ordinate in Figure 9-14. The corrected value is the masked threshold at f if the value is more than 20 dB above the absolute threshold at f. If it is less than 20 dB, a correction must be made for non-linearity in the masking versus noise level function near the absolute threshold. To correct for masked threshold below 20 dB absolute threshold, use the curve in Figure 9-15.

The effect of masking on evaluation of loudness function has been studied recently (92). Techniques for the improvement of signal to noise ratio by altering the signal or by filtration of masking noise are available (66).

Localization of Sound

Localization of sound appears not to be a significant problem in space operations. A Naval study has been directed to this subject (8).

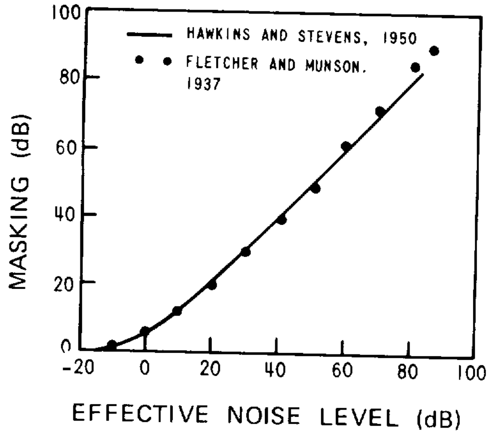


Figure 9-15

Masking as a Function of Noise Level in the Critical Band

(After Gales et al(66))

SPEECH

The vibration of the vocal cords or resonance of the air column in the mouth and nasal passages determines the nature of speech. Speech patterns may be quantitated by recording instantaneous speech pressure with time or by determining the rms speech pressure at a given frequency band in a stated time interval. Much of the material in this section is taken directly from a fine review of speech physiology (120). Data are currently being gathered on typical astronaut speech patterns (188, 189); on the characterization of speech sources in terms of genetic operating characteristics (178); and on the words used most frequently in aerospace communications (49).

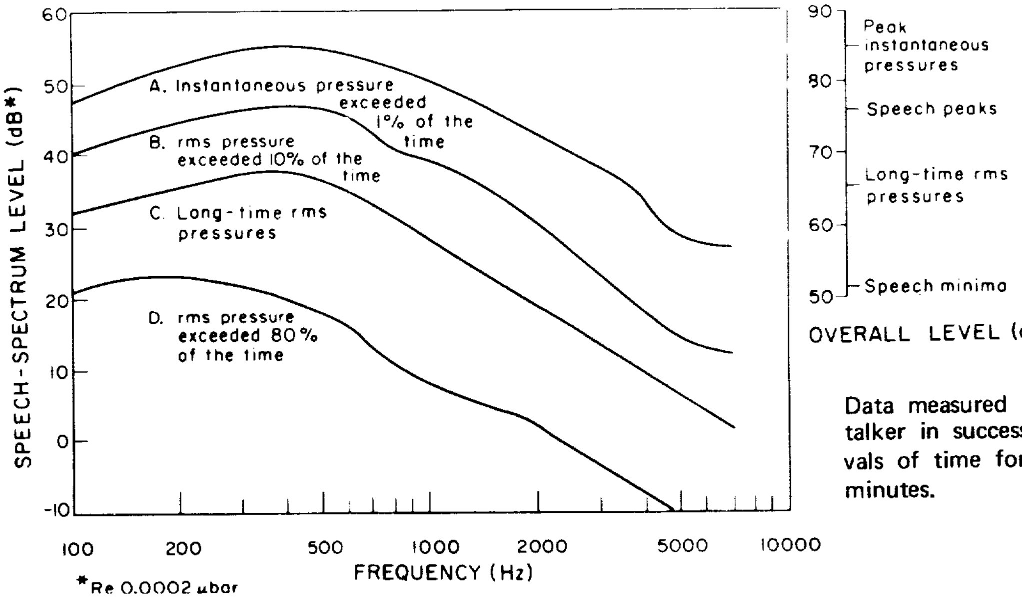
Speech Spectra

When filters one-octave wide are used, the function relating the spectral coefficients to the center or boundary frequencies of the octave is called the octave-band spectrum. It often simplifies a calculation, dimensionally, to divide the rms pressure in each band by the width of the band in cycles per second (Hz). When that quotient is translated into decibels, the result is called the spectrum level. An overall level of speech covers the spectrum across the audio-frequency range. Typical octave-band spectra of adult males are available (66). The overall speech level is 65 dB relative to 0.0002 μbar, a representative level for male speakers using a moderate level of vocal effort. The spectrum produced by female speakers is roughly similar in shape, but the overall level of female speech is, on the average, 2 or 3 dB lower.

For some purposes it is important to examine changes of speech pressure with time while simultaneously retaining the analysis of the speech wave into several or many bands of frequency. One way of accomplishing this is to divide the speech signal into a number of frequency bands (by means of band-pass filters) and then to divide the component signals - the individual signals in the several bands - into segments of 1/8-sec duration.

Measurements have been made in the manner described above with octave band and half-octave-band filters. The maximum instantaneous pressure in each 1/8-sec segment, and, also, the rms pressure in each 1/8-sec segment are determined. Spectrum levels are derived by dividing the squares of the instantaneous pressure and the rms pressure by the filter band-width and then converting the quotients into decibels.

Four curves relating sound-pressure level to frequency are shown in Figure 9-16. Curve A shows, for each frequency band of 1 Hz width, the instantaneous pressure that was exceeded in only 1 percent of the 1/8-sec intervals. This curve is, in a sense, a "peak-instantaneous-pressure" curve. Curve B shows, for each frequency band, the root-mean-square pressure that was exceeded in only 10 percent of the 1/8-sec intervals. One can call this one the curve of "speech peaks." Curve C is the long-time-rms pressure Curve D shows, for each frequency band, the rms pressure that was exceeded in 80 percent of the 1/8-sec intervals. Inasmuch as about one-fifth of ordinary conversational speech is dead time, this lowermost curve represents, in a sense, the rms pressure of the weakest sounds. One can refer to this curve as the "speech minima" curve. At the right-hand side of the graph are represented the corresponding overall levels - the values for unanalyzed, unfiltered speech.



Data measured one meter from the talker in successive 1/8-second intervals of time for a period of two minutes.

Figure 9-16

Spectrum Level of Instantaneous and RMS Pressures of Speech Uttered at a Conversational Level of Effort

(After Gales et al(66), from the data of Dunn and White(43))

If the speech is too soft, it will be masked by noise in the communication system. If it is too loud, it will overload the system. Dynamic range is the difference, in decibels, between the pressure level at which overload occurs (according to some overload criterion) and the pressure level of the noise in the system. Obviously, the dynamic range is not, in general, the same for all points in the communication system. Usually, it is the dynamic range at the listener's ear that is most important.

To determine the dynamic range required of a communication system, the engineer must take into account the variations in pressure level from speech sound to speech sound, condition to condition, and talker to talker.

Several key speech ranges have been noted from the weakest to the strongest (66):

- The range of fundamental speech-sound level is 0-28.2 dB.
- The range (difference) from speech minima with minimum normal vocal effort to peak instantaneous pressures with maximum normal effort is 60 dB (39-99).
- The range (difference) from speech minima to peak instantaneous pressures is about 40 dB for a given level of vocal effort.
- The range of variations of talkers in normal conversation is 20 dB.

Table 9-17 covers some of the typical speech levels 1 m from the talker.

Table 9-17

Sound-Pressure Levels of Speech 1 m from the Talker

(After Gales et al[66])

Measure of sound pressure	Whisper (dB)	Normal level (dB)			Shout (dB)
		Minimum	Average	Maximum	
Peak instantaneous pressures	70	79	89	99	110
Speech peaks	58	67	79	87	98
Long-time rms pressures	46	55	65	75	86
Speech minima	30	39	49	59	70

Critical design recommendations for dynamic range in speech communication have been recorded (66).

- For very high-quality communication, the dynamic range should be 60 dB.
- For commercial braodcast purposes, the dynamic range can be 40-45 dB.
- If a mechanism for compensating for variations in average speech levels among talkers is provided in the system, a dynamic range of 30 dB is adequate for essentially perfect speech communication.

- With practiced talkers and listeners, communication can be quite effective in a system providing a dynamic range of only 20 dB.
- Because most communication systems include microphones and/or background noise, it is appropriate to identify "normal" with 65 dB relative to 0.0002 μbar, one meter in front of the talker.

Intelligibility of Speech

In designing a speech-communication system, many design decisions must be made on the basis of the intelligibility of speech in a given system. Two procedures are available for measuring speech intelligibility. One procedure, the one the design engineer can use most often, is characterized by calculating a predictive measure of intelligibility. The other procedure involves measuring intelligibility directly through intelligibility testing.

Both of the above procedures have their limitations. For example, the calculated, predictive measure of intelligibility breaks down under extreme conditions of noise masking, frequency distortion, and certain kinds of amplitude distortion and is not applicable to the evaluation of systems involving complex processing of speech. When confronted with such problems, it is necessary to resort to empirical data derived from intelligibility tests to provide the basis for engineering decision, but intelligibility testing requires careful laboratory methods involving the control of a number of factors (45, 55, 59). (An aerospace word list is available (49).

Articulation Index (66)

Many design decisions can be made on the basis of calculated, predictive measures of intelligibility. One such measure is the articulation index (AI), and there are two methods of calculating it; one (the 20-band method) is more detailed and accurate than the other (the weighted-octave-band method). A second measure is really an inverse measure of intelligibility and is called the speech inference level (SIL) of noise. The articulation index should be used in all carefully designed speech-communication systems. The speech interference level can serve as a rule-of-thumb guide in making some engineering decisions regarding face-to-face communication.

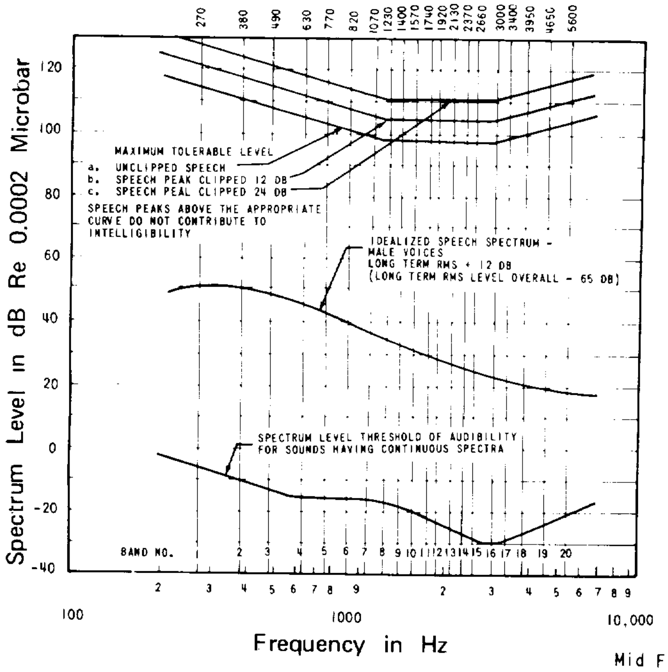
For speech-communication systems, the AI can be used as the predictive measure of intelligibility. The articulation-index formulation is based on the fact that, to obtain high intelligibility, one must deliver a considerable fraction of the total speech band-width to the listener's ear and, also, that the signal-to-noise ratio at the listener's ear must be reasonably high. If the speech peaks are 30 dB or more above the noise throughout the frequency band from 200-6,000 Hz, the listener will make essentially no errors (AI = 1.00). If the speech peaks are less than 30 dB above the noise in any part of the speech band, the listener will make some mistakes (AI < 1.00). If the speech peaks are never above the noise at all (ratio of speech peaks to rms noise less than 0 dB), the listener will rarely be able to understand anything (AI = 0).

Details regarding the establishment of the AI index by the two major methods and variants under different noise conditions are available (2, 10, 11, 25, 43, 59, 66, 113, 118, 154, 204). Figure 9-18a is an example of the basic worksheet for the 20-band method giving the baseline data needed. Figure 9-18b is an example of the calculation of the AI by the 20-band method

Figure 9-18

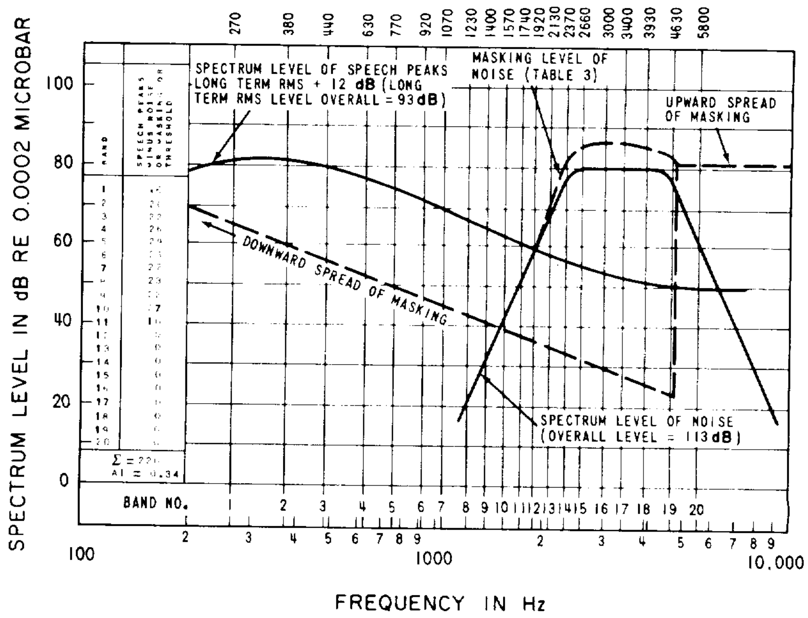
Calculation of Articulation Index by the 20-Band Method

Mid Frequencies of 20 Bands Contributing Equally to Speech Intelligibility with Male Voices



a. Worksheet for the 20-Band Method

Mid Frequencies of 20 Bands Contributing Equally to Speech Intelligibility With Male Voice



b. Sample Calculation by the 20-Band Method from data on the masking level of a sample 113 dB noise (overall level) with upward and downward spread of the masking.

Speech-intelligibility test scores are influenced by a number of distortion and stress conditions imposed upon the speech signal during its transmission. The effects of a number of such factors can be quantitatively evaluated by the appropriate use or modification during use of AI (117). Further, the effect on speech intelligibility can be properly predicted by an AI when only one factor is present or when several such factors are operating simultaneously. AI's adequately predict either the effects of wideband, continuous-spectrum noise or the effects of bands of noise as narrow as 200 Hz wide, in the frequency range from about 200 Hz to 6000 Hz and for sound-pressure levels up to approximately 125 dB.

Speech may be masked by non-steady-state noise. The duty cycle is that fraction of the time that a masking noise is on and affects speech intelligibility (135). Whenever the noise is not steady-state and the on-off duty cycle is known, the appropriate effective AI can be determined by calculating the AI as though the noise were steady-state and then applying a correction to the resulting AI as indicated inFigure 9-19. This procedure may be followed where the noise falls during the "off" periods to a level at least 20 dB below the level of the noise during the "on" periods.

The rate of interruption of the noise is also to be considered. The effective AI found for a communications system in which a noise having a definite on-off duty cycle is present should be further adjusted in accordance with the functions shown in Figure 9-20. The vertical ordinate gives the effective AI to be expected for a given parameter when the masking noise is interrupted at the rates shown on the abscissa.

Frequency distortion, or the transmission of the signal with unequal gain as a function of frequency, usually affects the intelligibility of speech. These effects are accounted for with reasonable accuracy by AI provided that the unequal emphasis is applied to the appropriate frequency band component of the speech signal. However, the AI will not provide a valid means for estimating the intelligibility of speech that has a very irregular long-term spectrum, i.e., a spectrum that goes through a series of peaks and valleys, the slopes of which, on the average, exceed 18 dB/octave (119).

Amplitude distortion of the speech signal may also affect intelligibility. The effects of sharp symmetrical peak clipping (a noise-canceling method discussed below) can be estimated by use of a computed AI as follows (205):

(1) Determine from Figure 9-21 the increase in the long-term rms of speech as the result of the particular amount of peak-clipping and post-clipping amplification present in a system (205).

(2) Add the result of (1) above to the speech peaks (unclipped speech + 12 dB) that would reach the listener's ears without the peak-clipping and comparable post-clipping amplification. Post-clipping amplification is defined as the amount

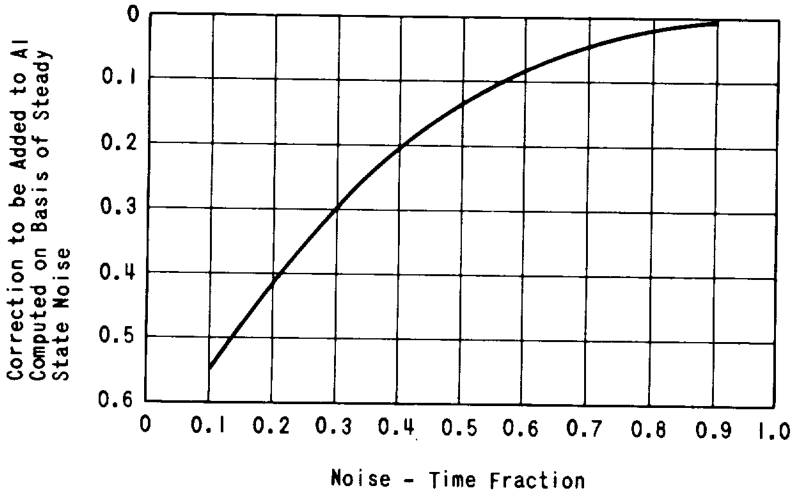


Figure 9-19

Correction of the Articulation Index for Intermittent Noise

The ordinate shows a correction to be applied to the articulation index computed on the assumption that a masking noise is steady-state for various noise-time fractions. The corrected AI cannot exceed 1.0

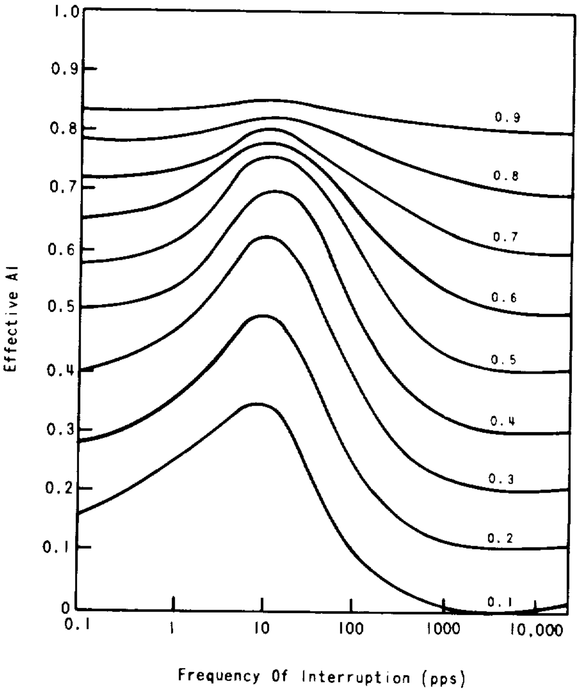
(After Gales et al(66), adapted from from Miller (135))

Figure 9-20

The Effective AI as a Function of the Frequency with Which a Masking Noise is Interrupted

The parameter of the curves is the corrected AI calculated on the assumption that the masking noise is steady-state and then adjusted according to Figure 9-18 for the fraction of the time the noise is on.

(After Gales et al(66), adapted from Miller and Licklider(137))



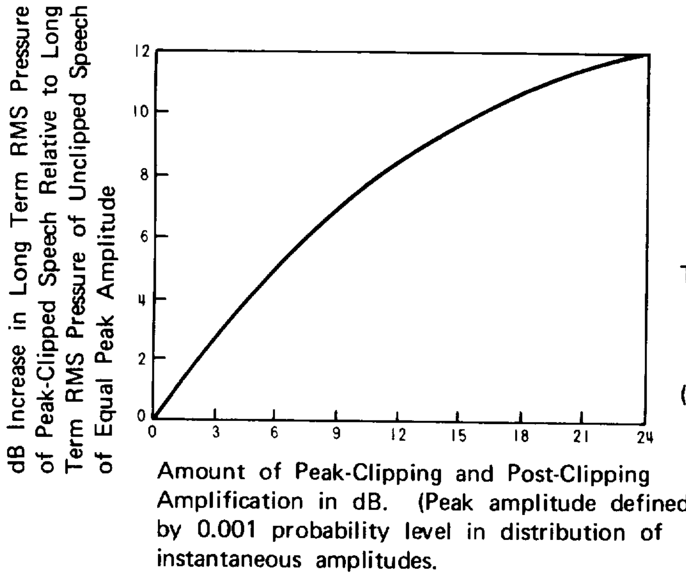


Figure 9-21

The Increase in RMS Speech Power as a Function of Clipping When Clipped Level is Raised to Clipping Reference Level

(After Wathen-Dunn and Lipke(205))

of amplification added to the system to achieve peak-to-peak amplitudes equal to the peak amplitudes that would be achieved without peak clipping. If the post-clipping amplification does not equal in decibels the amount of peak clipping applied to the speech signal, the increase in the long-term rms found in Step (1) should be reduced by a factor equal to the ratio between the decibel amount of peak-clipping and post-clipping amplification.

(3) Plot the result of Step (2), (Figure 9-18a) and proceed to compute AI as one would for continuous noise. Note that the maximum tolerable level indicated in Figure 9-18a worksheets for the speech is higher for peak-clipped than for nonclipped speech. In general, peak clipping will be used only when the speech signal is relatively free of noise prior to reaching the processing unit. (see below).

Reverberation in a room in which a speech signal is presented will cause a decrease in intelligibility (109). The amount of degradation will be a function of the reverberation time of the room. For present purposes, reverberation time is defined as the time required for a steady-state pure tone of 512 Hz to decrease 60 dB after the source is stopped. It is possible to correct the AI found for a given speech communication system when the reverberation time is known by the use of Figure 9-22.

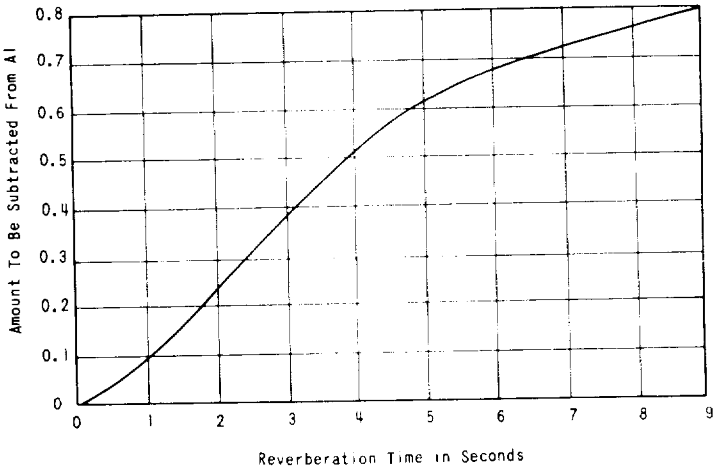


Figure 9-22

Effect of Reverberation Factors in the Intelligibility of Speech

The ordinate shows the amount to be subtracted from AI. AI cannot be less than 0.0.

(After Gales et al(66), from the data of Knudsen and Harris(109))

Very weak or very intense vocal efforts by a talker will tend to reduce speech intelligibility (153). A given AI value can be expected to be accurate, other factors held constant, when the vocal effort of the talker is maintained at a fairly consistent level somewhere between a measured long-term rms sound-pressure level with 50 to 85 dB measured one meter from the talker's lips. In systems where very strong or very weak vocal efforts are used the measured speech level should be changed into an effective speech level prior to the plotting of the speech spectrum on the AI worksheets. The relation between actual and effective speech levels is shown in Figure 9-23.

Visual cues from observing the talker's lips or face can contribute a great deal to the intelligibility of speech, particularly in the presence of noise (187). However, an AI can be modified or adjusted in accordance with Figure 9-24 into an "effective AI" to reflect the effect of visual cues upon speech intelligibility.

There are many other factors influencing speech communication that the AI as presently calculated does not evaluate. In particular, it should be noted that the method is designed for and has been validated principally against speech intelligibility tests involving male talkers. With what degree of accuracy AI would predict the relative intelligibility of speech of female talkers over different communication systems is not known. Also, the quantitative effects upon speech intelligibility to be obtained from listeners receiving a mixture

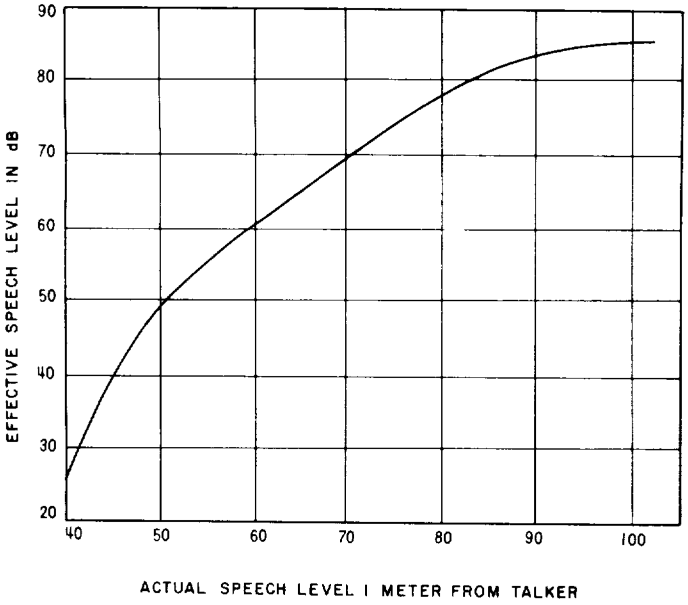


Figure 9-23

The Effective Speech Level as a Function of the Actual Speech Level Used by a Talker

Data are given as dB, long term (R.M.S.) re 0.0002 micro bars.

(After Gales et al $^{(66)}$)

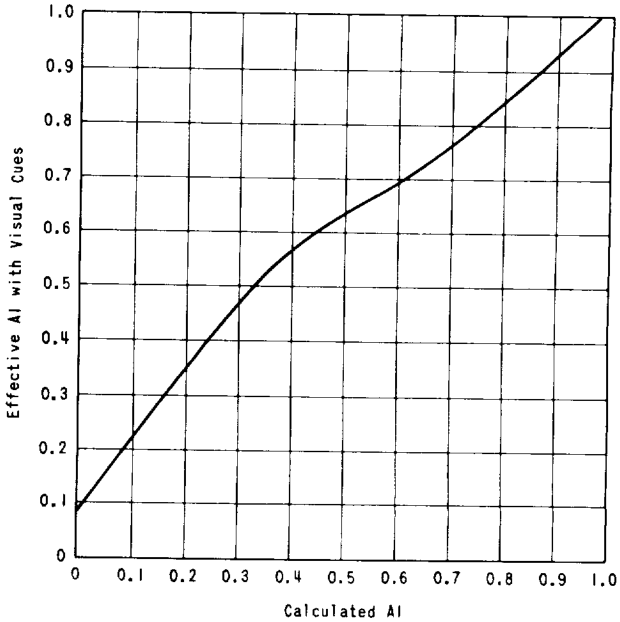


Figure 9-24

Effect of Visual Cues on Intelligibility of Speech

Relation between calculated AI and effective AI for a communication system wherein the listener can see the lips and face of the talker.

(After Gales et al$^{(66)}$, from the data of Sumby and Pollack$^{(187)}$)

of the speech signals directly from a talker and also from a loudspeaker are not known. Accordingly, AI should probably not be applied to such a system.

Conversion of AI to Speech Intelligibility Scores

AI's may be converted to estimated speech-intelligibility scores by use of Figure 9-25. It is to be especially noted that the intelligibility score (in percent correct) is highly dependent upon the constraints placed upon the message being communicated. The greater the constraints, i. e., the smaller the average information content (in information theory terms) associated with each item in the total ensemble of message, the higher the percent intelligibility score for a given AI. Typical constraints may consist of grammatical structure and context, such as found in sentences, limitations in vocabulary size, and in the syllabic length of words. See Ref.(49) for an aerospace word list.

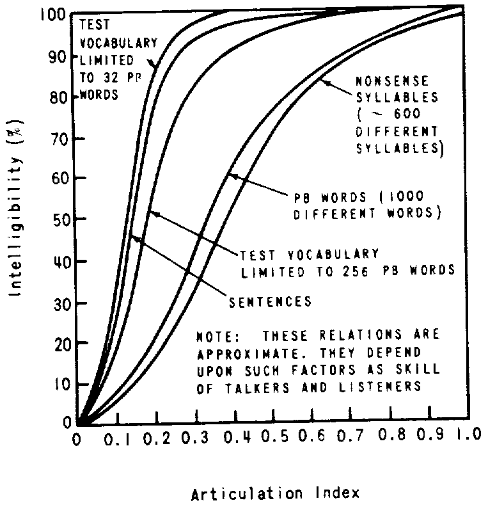


Figure 9-25

Relation Between the Intelligibility of Speech and the Articulation Index

(PB = phonetically balanced)

(After Gales et al(66), from the data of French and Steinberg(59))

No single AI value can be specified as a criterion for "acceptable" communications. The efficiency of communications as shown in Figure 9-25 is a function of the messages to be transmitted and the proficiency of the talkers and listeners involved. Furthermore, what level of performance is to be required over a given system is, of course, dependent upon factors whose importance can be evaluated only by the users of the communication system.

The Speech Interference Level (SIL)

A simpler, but less exact and less general method for predicting the intelligibility of face-to-face speech communication has been devised for use in situations where the noise has a relatively continuous spectrum (e. g., ventilation noise in offices, aircraft noise, the noise in most engine rooms, and the noise around milling machines) (66). The method, called the speech-interference-level (SIL) method, yields the maximum noise level that will permit correct reception of 75% of PB (phonetically balanced) words or about 98% of test sentences. This criterion is equivalent to an AI of about 0. 5.

To determine the SIL of a given noise, proceed as follows:

- Measure the sound-pressure level of the ambient noise in octave bands of 600-1, 200; 1, 200-2, 400; and 2, 400-4, 800 Hz.
- Determine the arithmetic average of the decibel levels in the three octave bands. This average value is the SIL.
- Consult Figure 9-26a to find the maximum distance between talker and listener at which 75% of PB words will be heard correctly. Figure 9-26b summarizes the use of SIL in estimating speech interference.

Figure 9-27 summarizes the intelligibility of speech as related to the ignal-to-noise ratio (see also Figure 9-33). In those situations where a ow signal-to-noise ratio is unavoidable the use of standardized phrases or words may mean the difference between satisfactory and unsatisfactory perormance.

nterference with Speech by Secondary Environmental Factors

Simultaneous Speech

A listener cannot listen to two simultaneous and non-redundant messages and receive full information from both messages. Instead, he switches attention from one to the other, with an attendant loss of information in both messages. In paying attention to one and disregarding the other, only the one message is understood. When more than a one-voice message exists simultaneously in a communication situation, the use of frequency-selective filters can give characteristic timbres to each of the several voices, thereby permitting reception of the relevant voice.

Ambient Atmosphere

The human voice, earphones, and loudspeakers become less efficient generators of sound as the ambient atmospheric pressure is reduced. The effect on the talker, microphone, and earphone, of reducing the ambient pressure from that of sea level to that of 40, 000 ft is shown in Figure 9-28.

The effects of the gaseous composition, such as the helium content of the atmosphere, on sound propagation and intelligibility of speech is covered in Inert Gas (No. 11).

Ear Plugs and Helmets

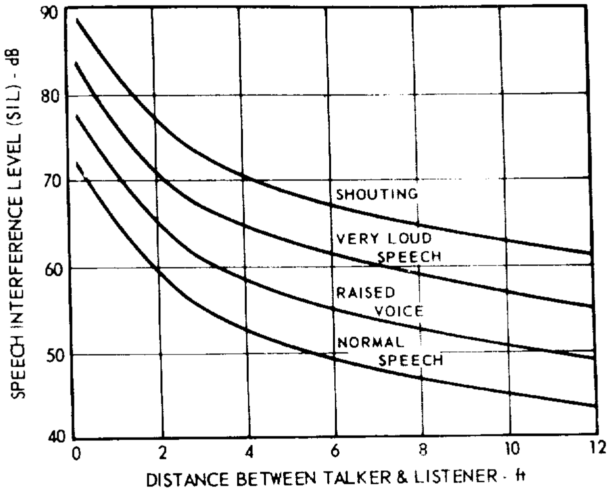
Under most noise conditions, a listener can wear ear plugs without reducing the intelligibility of speech. Ear plugs attenuate the speech and the noise by the same amount so that the signal-to-noise ratio at the listener's eardrum is the same with the ear plugs as without them. When speech level exceeds 85 dB, ear plugs cause an increase in intelligibility, whether or not there is background noise. This is depicted in Figure 9-29. The noise reduction by typical helmets is seen in Table 9-50c and in Figures 9-51 and 52.

Figure 9-26

Speech Interference Levels

(After Jerison(104), data for graph from Gales et al (eds.)(66)),
table from Rosenblith and Stevens(166))

a.



Speech Interference Level (SIL) is a readily calculated index of the degree to which a complex sound or noise will interfere with speech. It is also often used as a rough estimate of the comfort or acceptability of a potentially annoying noise. SIL is defined as the arithmetic mean of the sound pressure levels (dB re 0.0002 dyne/cm^2) within three octave bands: 600-1200 Hz, 1200-2400 Hz, and 2400-4800 Hz. The chart shows the maximum permissible SIL for normal and raised speech associated with various distances between speaker and listener. It should be kept in mind that the SIL is accurate only for broad-band noises with fairly typical spectra. With atypical noises such as those shown by the Mercury astronaut curve in (9-3) SIL may not be strictly appropriate, but will probably be used until better measures are developed.

SIL of the noise estimated at the astronaut's ear during lift-off may be calculated from the dB levels within the three octave bands between 600 and 4800 Hz as shown in 9-3. These are 81, 60, and 41 dB. SIL is the arithmetic mean of these numbers; therefore, SIL = (81 + 60 + 41)/3 = 61 dB. For the Century fighter overflight shown in 9-10c, SIL = (118 + 113 + 108)/3 = 113 dB.

Speech communication criteria associated with various SIL levels are shown in the following table:

b.

Speech Communication Criteria

SIL dB	Voice Level and Distance	Nature of Possible Communication	Type of Working Area
45	Normal voice at 10 ft.	Relaxed conversation	Private offices, conference rooms
55	Normal voice at 3 ft; raised voice at 6 ft, very loud voice at 12 ft.	Continuous communication in work areas	Business, secretarial, control rooms of test cells, etc.
65	Raised voice at 2 ft; very loud voice at 4 ft; shouting at 8 ft.	Intermittent communication	
75	Very loud voice at 1 ft; shouting at 2-3 ft.	Minimal communication (danger signals, restricted prearranged vocabulary desirable)	

Figure 9-27

The Role of Signal-to-Noise Ratio in Speech Intelligibility

(Adapted from Jerison(103); (a) after Pollack(158); (b) after Miller et al(136); and (c) after Gales et al(66))

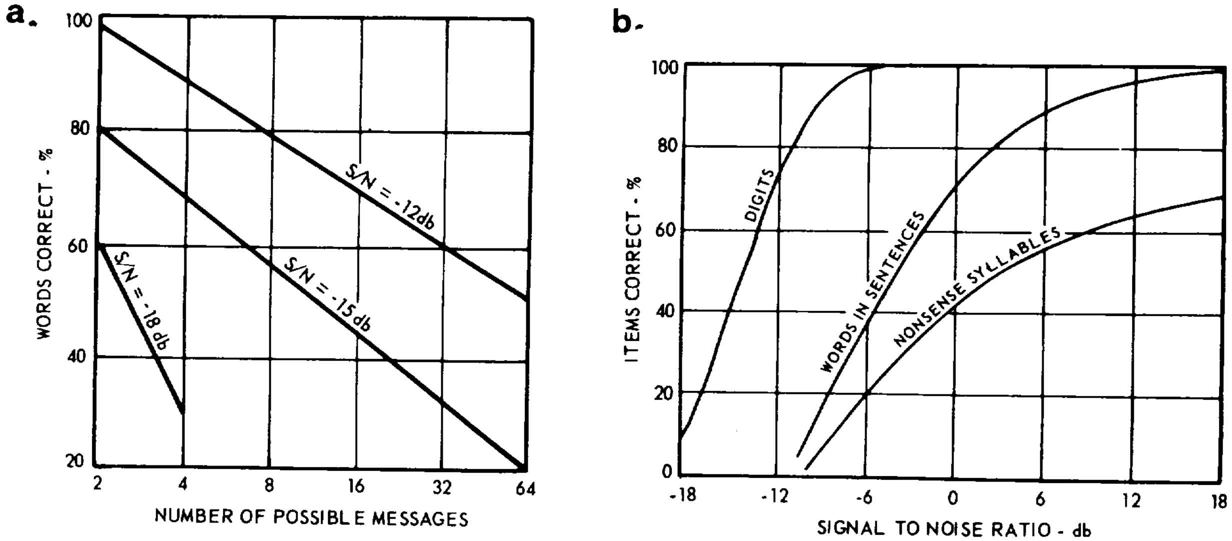
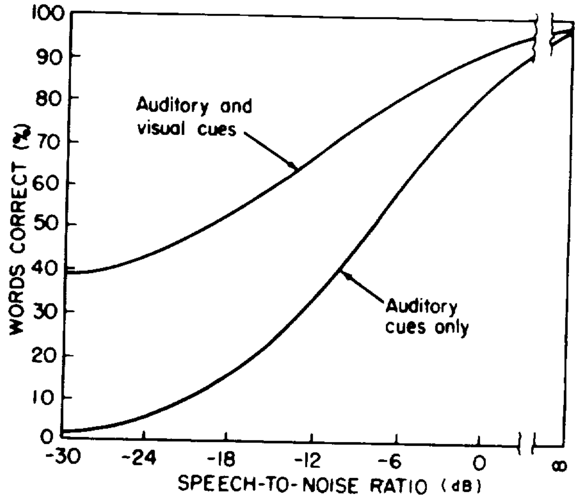


Figure a shows how the correct perception of spoken messages is affected by the diversity of responses required of the observer. As the number of possible messages (standard, two-syllable words) increases from 2 to 64, the percentage of correct reports about the messages drops. The relationship is poorer when the signal/noise ratio, shown here in dB, is lower.

Figure b shows similar effects with other materials graphed in a different way. It shows that single numbers (digits) are detected correctly more easily than are words in sentences, and words in sentences are detected correctly more easily than nonsense syllables. This is a special case of the effect shown in figure a. In General, the less "information" the sender-receiver system has to process, the more accurate the processing. In figure a, the system is processing from 1 to 6 "bits" of information (that is, 64 messages = 2^6 messages = 6 "bits"). In figure b, the amount of information processed varies from a little over 3 "bits" for digits to unknown but higher amounts for the other categories. It is clear that communications can be improved by using a limited vocabulary: the smaller the vocabulary, the better the system.

Figure c shows that the increment of inteligibility contributed by visual cues is a function of the prevailing speech-to-noise ratio; if the speech-to-noise ratio is high, the listeners hear the words clearly and therefore cannot take advantage of the cues provided by lip reading; if the speech-to-noise ratio is low, they need, and they in fact use, the visual cues.



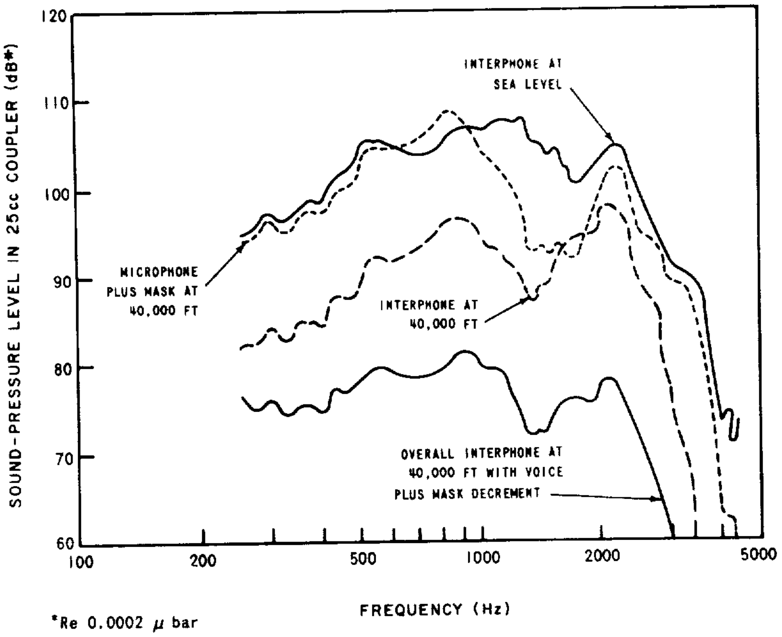
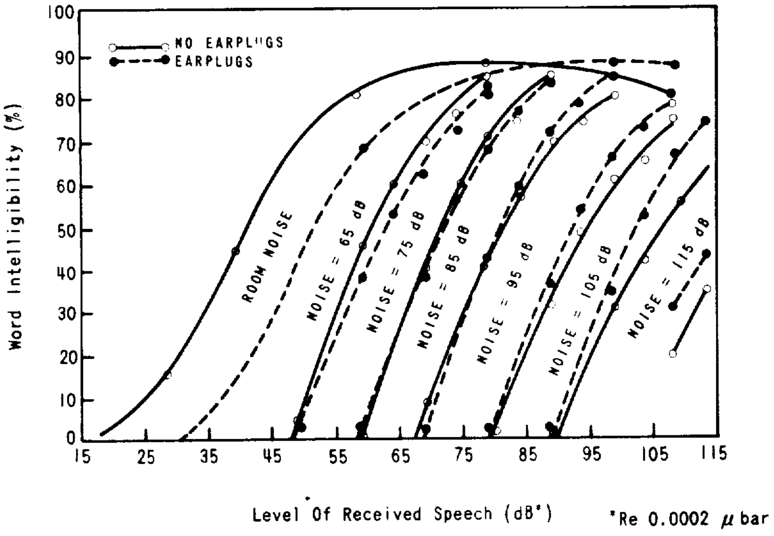


Figure 9-28

Effects of Ambient Atmospheric Pressure on Reception of Speech at Sea Level vs 40,000 ft (2.7 psia or 141 mm Hg)

(After Kryter(110))



Relation between PB-word intelligibility and speech level in various levels of masking noise with and without ear plugs. (NDRC type V51R ear plugs were used). Data show higher intelligibility in presence of intense noise with ear plugs than without.

Figure 9-29

Effects of Ear Plugs on Intelligibility of Speech

(After Kryter(113))

Speaker Training

Considerable increases in intelligibility are found whenever trained talkers are used to convey auditory information. This increase in intelligibility is more marked under noisy conditions than under more optimal ones. Characteristics which differentiated good from poor talkers are as follows:

1. Superior speakers speak with greater syllable intensity (decibels).
2. Superior speakers have longer average syllable durations.
3. Superior speakers have more pitch variability than poorer ones.
4. Superior speakers utilize proportionally more of total speech time with speech sounds and less with pauses.

Microphone and Electronic Processing in Speech Intelligibility (66)

Microphones are usually designed with the following characteristics:

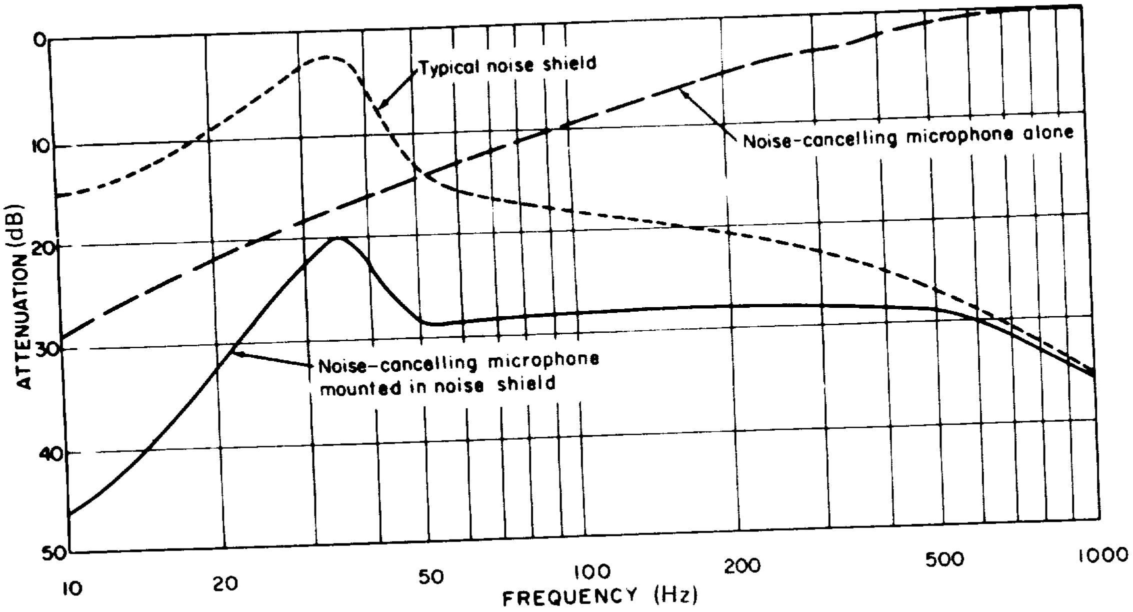
1. High sensitivity to acoustic speech signals.
2. Faithful transduction of the acoustic speech signal into an electric signal.
3. Ability to reject other acoustic signals and noises that are present at the location of the talker.

When the talker is in an intense noise field and the required space is available, the microphone should be put in a noise shield. A noise shield protects the microphone more from high-frequency than low-frequency noise; noise canceling does just the opposite. As shown in Figure 9-30a, a noise-canceling microphone in a noise shield can attenuate noise by 30 dB.

Many microphones are satisfactory insofar as frequency-response characteristics are concerned; few, however, are specifically designed to discriminate between the talker's speech signal and the ambient noise surrounding the talker. Microphones that are so designed are called noise-canceling microphones (90, 66). These microphones, also called differential or pressure-gradient microphones, are so constructed that sound waves can reach the diaphragm from the back as well as from the front of the microphone. When a microphone is placed directly in front of the lips of a person who is talking, it is in the spherically expanding part of the speech wave pattern, and there is a large gradient of speech pressure between the front and back of the diaphragm. Noise, on the other hand, usually comes from more distant sources. With noise-canceling microphones, this noise has equal access to both the back and front of the diaphragm and is thus largely "canceled" whereas the speech is not. The amount of discrimination that is available from a typical noise-canceling microphone placed 1/2 in. in front of the talker's lips is shown in Figure 9-30b. Noise-canceling microphones

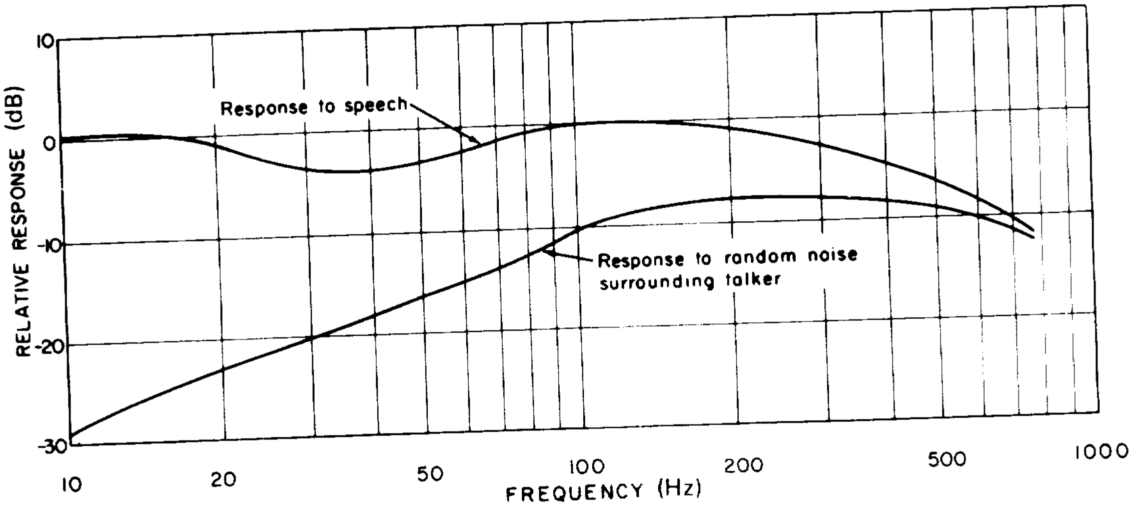
Figure 9-30

Noise Attenuation and Speech Intelligibility with Noise-Shielding and Noise-Canceling Microphones



a. Attenuation of Noise with Noise and Noise-Canceling Microphones

(After Hawley and Kryter(90))



b. Relative Response of Noise-Canceling Microphones to Speech and Noise When Placed 1/2 Inch from Speaker's Lips

(After Gales et al(66))

must be held very close to the lips if the noise discrimination properties are to be realized; in most cases they should just touch the lips when being used.

Amplifiers, transmitters, and receivers to be used in speech-communication systems should have the following characteristics (66):

1. Sufficient band-width to provide a "flat" audiofrequency response from at least 250-4,000 Hz (preferably 200-6,100 Hz for intelligibility and 100-7,500 Hz for quality of reproduction).
2. Sufficient dynamic range and gain to handle the range of instantaneous pressures found in speech and to develop the necessary signal level at the headset or loudspeaker terminals. In addition, they should introduce less background noise than is introduced by the microphone.

Linear amplification is usually desirable for speech communication when both talkers and listeners are in relative quiet. In noise, however, it may be desirable to introduce nonlinearity deliberately. Two kinds of nonlinear amplification are of particular interest in this connection: automatic gain control (AGC), sometimes called automatic volume control (AVC); and peak clipping.

Automatic gain control and peak clipping have different actions and effects, but they can be used together. The one essential difference in the actions of the two is in their response times; ordinary AGC operates on relatively long-time measures of the intensity of a signal whereas a peak clipper can be thought of as an AGC that operates instantaneously.

The AGC system derives a measure of the average signal strength over a period of time, and this information is used to adjust the operating characteristic of the amplifier. Sustained, intense signals lead to reduction of the gain; sustained, weak signals lead to increase of the gain. The average output level is, therefore, about the same, no matter what the average input level. But AGC does not eliminate variations in intensity between parts of the signal that occur together in a short interval of time; the consonants remain weaker than the neighboring vowels, for example, because the AGC averages over an interval longer than a single speech sound.

A noise-controlled AGC system can provide high speech intelligibility during periods of intense noise and, at the same time, protect the hearing of the listeners from exposure to intense speech during periods of relative quiet.

The attack-and release-time constants usually employed in the "limiter" amplifiers used in commercial broadcast work are, typically, 10 msec and 600 msec, respectively. For some communication systems designed to operate in noise, it has been found that an attack time of about 0.1 sec and a release time of about 10 sec are most satisfactory. (When the release time is made appreciably shorter, there is an objectionable fluctuation in the transmitted background noise).

Peak clipping is simply clipping the peaks off the speech signal and leaving the remainder (66). Ordinarly, peak clipping involves clipping both the positive (upward) and negative (downward) peaks. For all practical purposes, peak clippers have no attack or release times; they operate instantaneously. Peak clipping alone often tends to reduce the amplitudes of the intense parts of speech (usually the vowels) down to the level of the weaker parts (consonants). Because of this, peak clipping is often used to make the various speech sounds more homogeneous in amplitude. If by reamplifying a signal that has been clipped so that the peak amplitude of the remnant is the same as the peak amplitude of the original wave before clipping, the intensity of the weak consonant sounds is increased. This is true even though the peak level of the speech and therefore, the peak power requirements of the amplifiers, radio transmitters, etc., is not increased. Figure 9-31 shows word intelligibility as a function of peak amplitude of received speech, with peak

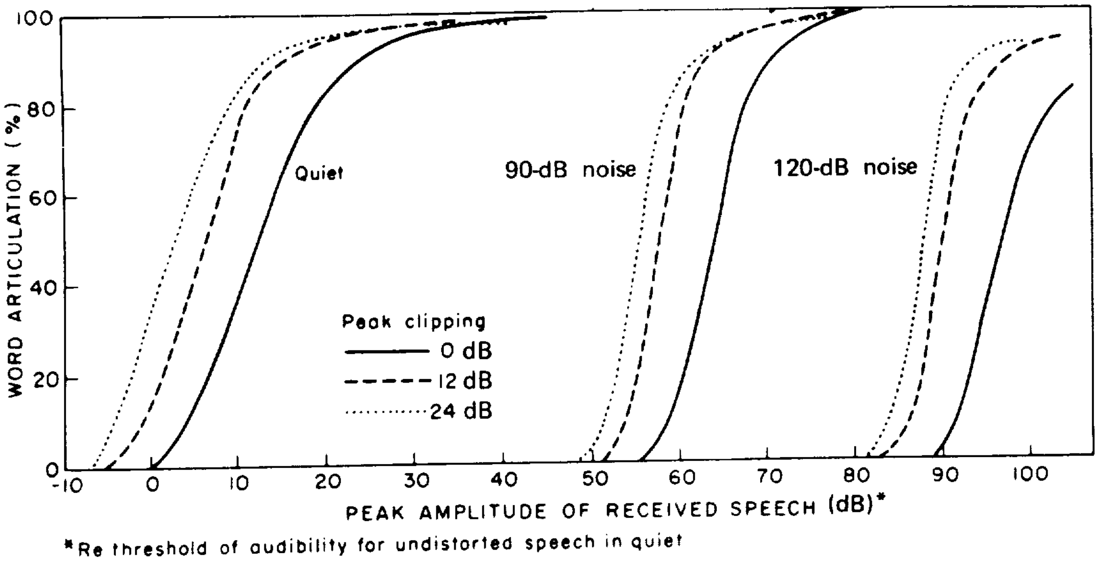


Figure 9-31

Word Intelligibility as a Function of Peak Amplitude of Speech with Various Levels of Peak Clipping

(After Gales et al(66), from the data of Licklider(126))

clipping as the parameter. As can be seen, with equal peak-to-peak amplitude, clipped speech is much better understood than unclipped speech.

The clipped speech in a quiet environment has a harsh, unpleasant sound because of the distortion products that are introduced by the clipping. When listened to in noise that enters the system at a point following the clipper, the distortion products tend to be masked by the noise, and the speech sounds about as "clean" as unclipped speech in the same noise. Data are available on the optimum level of clipping for various noise conditions and electronic configuration in the communication system (66).

Calculation of the effect of peak clipping on the articulation index has been covered in Figures 9-18a and 9-21. Another way of avoiding some of the distortion products introduced by peak clipping is by using the heterodyne clipping. A single-sideband, suppressed-carrier modulation is used to shift the spectrum of the speech signal up the frequency scale by x Hz. The peaks are clipped and the sideband-modulated carrier is reamplified by the desired amount. By then passing the resulting signal through a bandpass filter (x to x + 5,000 Hz) and using the signal in an ordinary single-sideband suppressed-carrier transmission or, if an audio signal is required, demodulating with the aid of standard single-sideband suppressed-carrier technique, the clipped speech may be transmitted.

Because the distortion-product noise introduced by peak clipping consists of harmonics and intermodulation products, it will be largely very high and very low in frequency, relative to the shifted speech frequencies, and will, therefore, fall outside of the band of the bandpass filter (x to x + 5,000 Hz), and the transmitted signal will not contain the distortion products even though it has been clipped. Such a process will make the received signal sound "cleaner" and less harsh to a listener in quiet. Elimination of the distortion products that lie outside the filter bands, however, will affect the shape of the transmitted wave in such a way that less power is actually transmitted than would be transmitted by an ordinary pre-modulation peak-clipping system. Thus, heterodyne clipping does not improve the intelligibility of the speech received in noise quite as much as does peak clipping the speech prior to modulation.

Standardization of earphones and equipment for audiometric testing is under study. New approaches to the study of speech audiometry are underway (186, 212, 214). For the Apollo program it has been suggested that the microphones and earphones have the following characteristics (198):

a.	Microphones	
	Output Level	0 dbm ± 3 dB into a 600 ohm load for sound pressure level (SPL) of 106 dB 1/4 inch from the microphone.
	Power Supply	14.0 to 20.5 volts.
b.	Earphones	
	Output Level	At least 110 dB SPL (Reference 0.0002 dyne/cm^2) for 0.78 volts RMS drive into a 6 cc cavity.
	Input Impedance	600 ohms.
	Minimum Power	15 mw

BIOLOGICAL RESPONSES TO NOISE EXPOSURE AND TOLERANCE

The human response to noise has received recent review (68, 71, 82, 112, 138). The responses may be considered from the physiological and psychologic point of view.

Physiological Effects of Noise

Ear and Hearing

The primary effects of noise exposure are on the hearing organ and on the hearing function. Loudness perception, masking of other signals by noise, temporary hearing loss after occasional exposure to higher sound pressure levels, and finally permanent hearing loss caused by repeated exposures to noise for days and years, have been studied extensively in connection with the large scale problem of industrial noise exposure (114, 172). The gradual cumulative loss of hearing is apparently due to degeneration of the external hair cells in the cochlea and depends on the level of the noise, its frequency spectrum, the intermittency of exposure, the age and probably the susceptibility of the individual (122, 164).

Discomfort to the Ear

When a sound of high intensity (especially at low frequencies) enters the ear, a number of protective mechanisms come into operation to reduce the amplitude of vibration at the hearing organ (82). The immediate effects include a change in the mode of vibration of the stapes, due to subluxation of the incu-stapedal joint and, under extremely intense stimulation, the malleo-incudal joint. The foot of the stapes then performs a rocking motion in the oval window, the amplitude of the piston-like movement being reduced. Some acoustical energy is also dispersed by the excitation of harmonics in the transmission pathway medial to the tympanic membrane.

As an additional protective mechanism, the stapedius and tensor tympani muscles contract in response to a loud noise (or mechanical irritation of the external auditory canal, face, or neck). Anatomically, these little muscles have opposing actions: stapedius tends to withdraw the foot of the stapes from the oval window, while tensor tympani tends to pull the handle of the malleus (attached to the eardrum) inwards. The resulting effect of these actions is to produce an increase in stiffness and possibly in damping of the ossicular chain. Because the muscular action of the acoustic reflex is a physiological response with a latency of some 10 msec, it fails to protect the hearing organ from noises which are impulsive or of sudden onset (e. g., gunfire).

Intense noise (SPL greater than 100 dB re 0.0002 μb), especially when it is of sudden onset, can provoke a generalized reflex response of tensing, grimacing, and covering the ears with the hands (86). In some individuals there is a compelling urge to avoid or escape from the noise.

Extremely high intensities of noise (> 135 to 140 dB) in the range of 20-2,000 Hz produce sharp pain in the ears, presumably due to stretching of the tissues of the eardrum and related structures, rather than to oversimulation of the hearing organ itself. It can be provoked in the totally deaf (1). For 15 Hz and below, 179 dB is the probably pain threshold (70). (See below).

Figure 9-32 represents the threshold for aural pain with high sound pressures. The following considerations apply to discomfort experienced from high intensity sound:

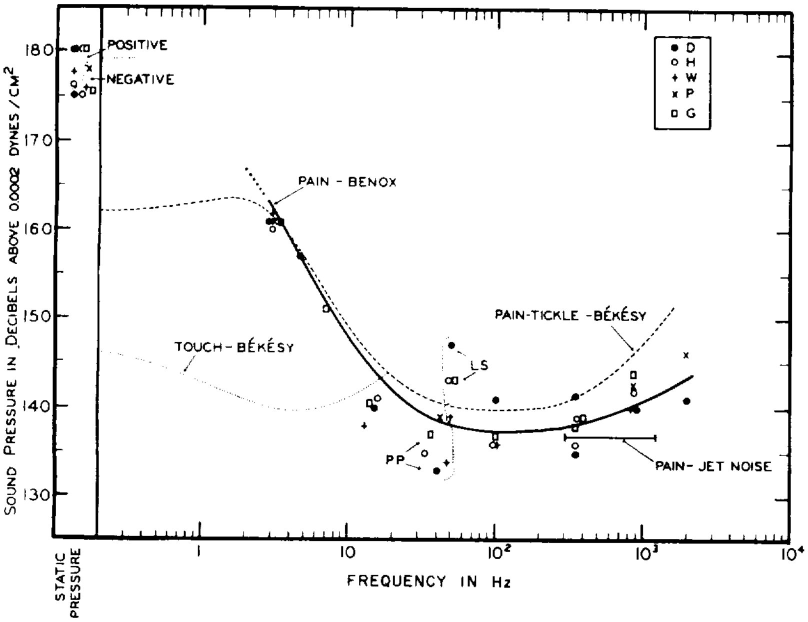


Figure 9-32

Thresholds for Aural Pain Produced by Pure Tones and Jet Noise

Points represent means of 3-4 determinations. Duplicate points represent means taken on different days. Positive and negative static pressures in the external ear canal are referred to atmospheric pressure. Line representing jet noise threshold is placed at overall sound pressure level and extends to the frequencies of the octave bands (300-600 and 600-1200) carrying most of the sound energy. (Touch and Pain-Tickle thresholds after Bekesy) (From reference 70). Solid line represents new contours proposed by CHABA Working Group 46. Broken line Glorig (A.A.O.O.), proposed by ISO (75).

(After von Gierke(68))

- Discomfort in the ear is felt after a few seconds exposure to noise fields exceeding 120 dB in the octave bands between 300 and 9,600 Hz.
- Annoyance is greater by a noise that is modulated in frequency and/or intensity than by a steady-state noise.
- Adaptation is greater to steady noise than it is to intermittent or irregular noise.
- Discomfort is avoided by setting a signal, whenever possible, at about 40-50 dB above absolute threshold.

Ear Damage - Temporary and Permanent Hearing Loss

Aftereffects of noise include temporary or permanent loss of hearing (112, 115). Good data have become available relating noise-induced permanent threshold shift (NIPTS) to broad-band steady noises experienced daily for eight hours over many years. The gap in knowledge with respect to intermittent, irregular exposures and short duration exposure has been filled by the plausible assumption, supported by various bits of indirect evidence, that noise-induced temporary threshold shift (NITTS), i. e., auditory fatigue and complete recovery following each individual noise exposure, is an integral part of the NIPTS process (see Figure 9-33). Without NITTS no NIPTS will develop. The assumption now is that NIPTS progresses similarly to NITTS but with a different time scale. All types of noise exposures which produce equal amounts of NITTS are considered equally hazardous with respect to NIPTS. The relative effectiveness of different noise spectra and different exposure time patterns can, therefore, conveniently and without hazard, be studied in laboratory experiments on normal-hearing subjects (75).

The NITTS can be measured with pure tone audiometry (36, 73, 107). Figure 9-33a and b covers the NITTS as related to steady and pulsed noise. Figure 9-33c relates temporary loss to NIPTS. The NITTS found in young adults with normal hearing, from an eight-hour exposure to a noise has about the same numerical magnitude as the NIPTS in industrial workers exposed for 10 or more years, eight hours per workday, to about the same noise (112). NITTS data can be used as a reasonably valid secondary yardstick for assessing the potential damage risk for permanent threshold shifts due to exposure to noise. Figure 9-33d shows how loss of speech intelligibility is related to hearing loss. A detailed analysis of the relation of NITTS and NIPTS to speech intelligibility is available (112).

In considering the permanent hearing loss, one must be concerned with the effects of short-term (under 8 hours) and long-term (over 8 hours) exposures to pure tone, narrow-band, and broad-band noise which can cause temporary or permanent damage to the ear. Several new approaches have been recently suggested (68, 112, 139). These damage contours are discussed below under noise control and protection, Figure 9-39 to 9-49.

The normal hearing loss associated with aging in males is recorded in Figure 9-34a (147). These curves exclude all men exposed to noise or military service where gunfire may have been involved, as well as those with a history of ear pathology. Theories on the cause of hearing loss in older individuals not exposed to excessive noise are currently focused on the changes in the joints of the ossicle chain of the middle ear which reduce the transmission of higher frequencies. Figure 9-34b presents the average hearing thresholds obtained by several surveys. The L. S. curve represents a special group of commercial and test pilots who appear to have lower thresholds than the general population (190). Astronauts would probably fall into this group.

Data are available on the hearing levels of adult Americans (74). Figure 9-34c represents an estimate of speech reception thresholds from these data obtained by averaging the levels at the three pure-tone frequencies which include the range usually considered most important for understanding speech-500, 1000, and 2000 cycles per second for the better ear. The patterns for men and women are similar. A steady increase with age from the youngest to the oldest age group can be noted in the estimated median thresholds for speech. Only in the age groups 60 years and over does the median threshold exceed audiometric zero. Some 8 percent of the adults in the U. S. A. or

Figure 9-33

After Effects of Noise

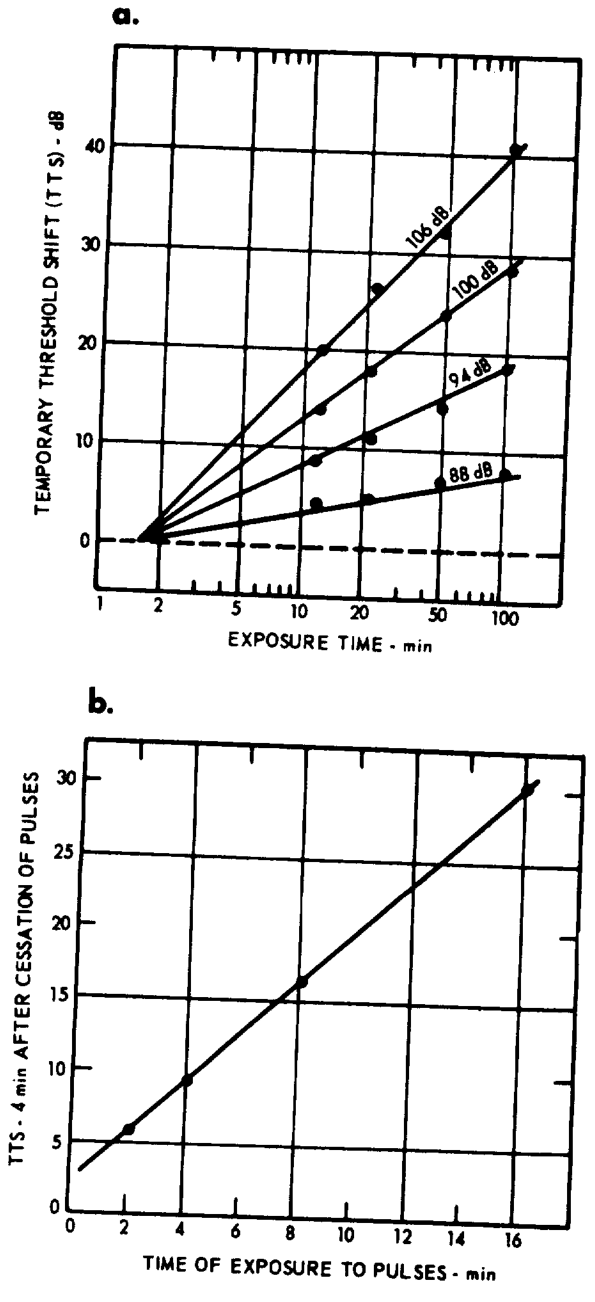


Figure a illustrates the increase in the amount of temporary threshold shift (TTS) for hearing a 4000 Hz tone as prior exposure to steady noise increases in duration. The effect is greater when the SPL of the noise is higher. For example, at 106 dB (top line) there is a more rapid increase in TTS than for the 100 dB noise, and so on. The amount of TTS is proportional to the logarithm of the duration of noise exposure.

Figure b illustrates the increase in TTS when the exposure is to an intermittent noise -- clicks at 25 per minute -- and at an SPL of 140 to 155 dB. The curve is the average of tests at 3000, 4000, and 6000 Hz; TTS increases linearly (rather than logarithmically) as exposure time increases.

(Figures a and b after Jerison(104), adapted from Glorig et al(75), and Ward et al(203))

Figure 9-33 (continued)

c.

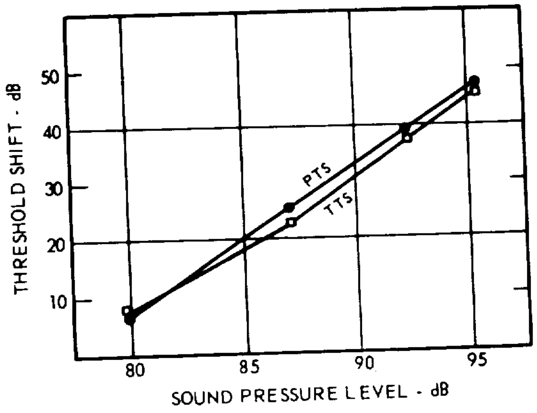


Figure c shows the relationship between TTS and permanent threshold shift (PTS) -- that is, partial deafness. The point in this figure is to emphasize that TTS, which is easily studied in the laboratory, is a valid measure of the permanent effect of a noise on hearing.

d.

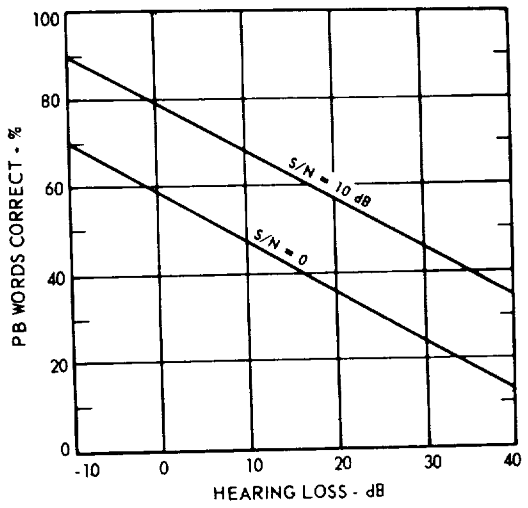
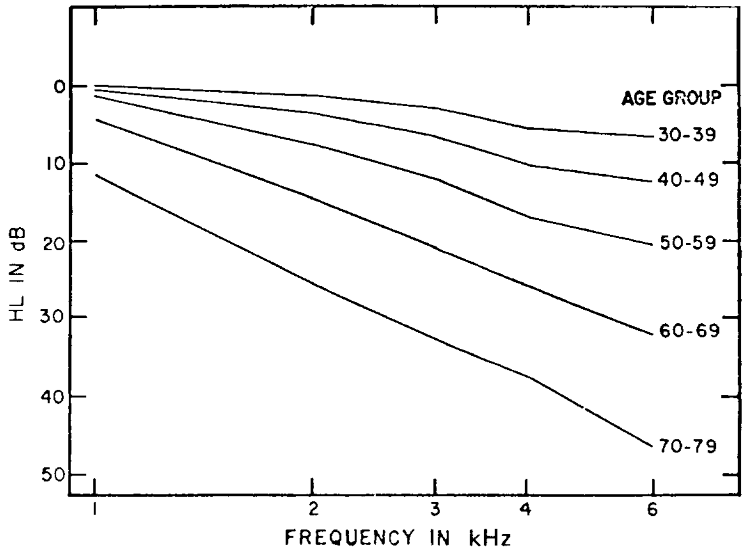


Figure d shows the relationship between partial deafness as measured by permanent threshold shifts (at 1000, 2000, and 3000 Hz) and the effectiveness of hearing for speech communication tested with PB (phonetically balanced) words. By combining the kind of information presented by these four charts, it is possible to set damage risk criteria as shown in Figure 9-40. The damage risk criteria are concerned with keeping permanent after effects of noise from damaging hearing, especially as used in speech communication.

(Figures c and d after Jerison(104), adapted from Glorig et al(75), and Kryter et al(121))

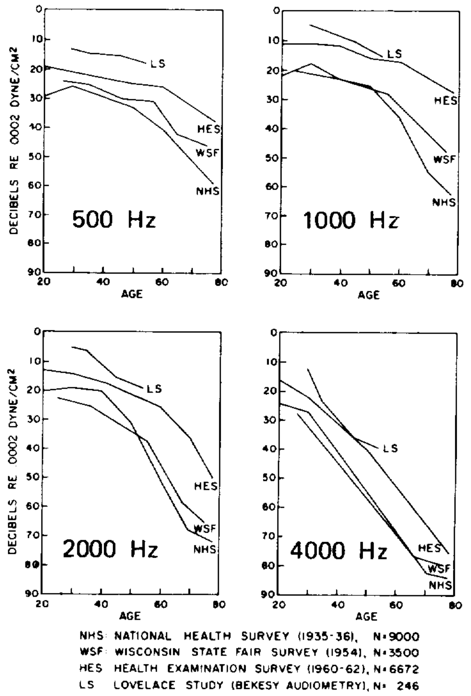
Figure 9-34

Loss of Hearing of Signals as a Function of Age



a. Hearing Loss of Tones in a Group of Males with No History of Ear Pathology or Exposure to Gunfire

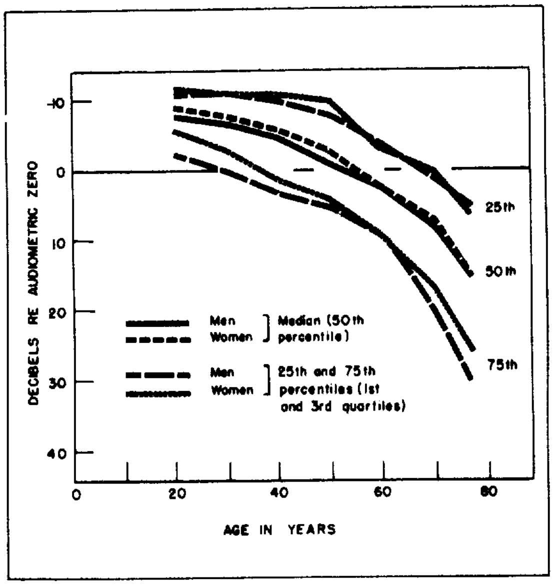
((After Nixon et al(147))



b. Comparison of Average Hearing Thresholds by Age at 500, 1000, 2000, and 4000 Hz for the "Better" Ear

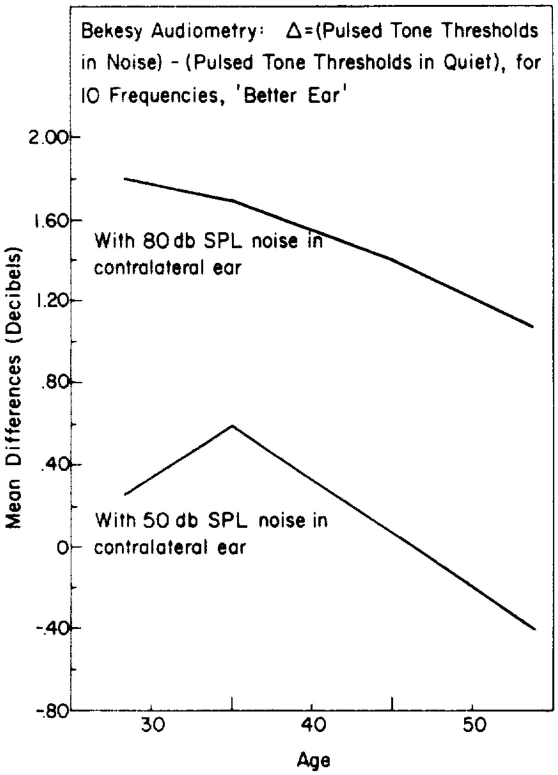
(After Szafran(190))

Figure 9-34 (continued)



c. Medians and Quartiles from the Distribution of the Hearing Threshold Level for Speech (Average of Pure-Tone Levels at 500, 1000, and 2000 Hz) in the Better Ear for Men and Women, United States

(After Glorig[(74)])



d. Bekesy Audiometry: Pulsed Tones Threshold at 10 Frequencies in the Better Ear of a Select Group of Pilots

(After Szafran[(191)])

9.2 million persons, have hearing levels in the better ear of 15 decibels or more above audiometric zero within the critical speech range. This includes persons with varying degrees of hearing handicap - ranging from some difficulty with faint speech to the inability to understand even amplified speech - which impairs their ability to hear everyday speech well enough to understand it.

In auditory perception studies using the Bekesy technique, many, though certainly not all older pilots of the L.S. curve of Figure 9-34b, do not show the traditionally expected unfavorable change of the effective threshold in the presence of 50-80 dB SPL white noise input to the contralateral ear (190, 191). The average difference between the pulsed tone thresholds in quiet and in noise for the better ear is plotted in Figure 9-34d.

Criteria for tympanic membrane rupture, when the ear is exposed accidentally to blast waves of different duration or to high intensity sound of varying duration, have been fully developed as a function of frequency, or pulse duration, or both (200). Levels above 155 dB for exposure to many sound cycles in the range of maximum ear sensitivity and above 175 dB for exposure to single blast pulses of low frequency content must be considered hazardous in this connection (34, 38, 94). (See also blast pathology in Pressure, No. 12).

Non-Aural Effects

During exposure to steady-state sound fields having an overall SPL of 120-150 dB or higher, undesirable, nonauditory effects are experienced, regardless of the ear protection provided (48, 82). Intense noise, especially at frequencies below 1000 Hz can be felt as well as heard. The threshold of feeling for airborne sound is some 10 dB lower than the threshold of aural pain in the middle audiofrequency range. By direct absorption through the body surface, airborne vibration can stimulate mechano-receptors throughout the body, including touch and pressure receptors and the vestibular organs. The sensations produced can be bizarre and disturbing. It has been suggested that, like mechanical vibration of the body, intense acoustical irradiation might interfere with postural activity, due to stimulation of the sensory pathways involved from several end organs (37, 38, 44).

The effect of high-intensity low-frequency noise on the respiratory system is reinforced in the 40-60 Hz range through mechanical resonance of the chest, the same resonance that determines the curve of safety criteria for emergency exposure of humans to blast waves of varying durations (17). Considering all such nonauditory mechanical effects on the body, it is important to keep in mind that dynamic mechanical response depends critically on body dimensions. Therefore, animal data are meaningless unless proper scaling laws have been applied (67). For example, the same chest resonance which occurs for human subjects between 40 and 60 Hz appears at over 400 Hz for a rabbit and at over 1,000 Hz for a mouse.

Vertigo and, occasionally, disorientation, nausea and vomiting can also be present. The order of sound pressure level necessary to provoke such symptoms is 120 to 150 dB re 0.0002 µb in the range 1.6 to 4.4 Hz (40, 44). Severe symptoms are likely to arise during acoustical stimulation at SPLs greater than 140 dB if the noise is predominantly of low frequency, below 10 Hz (Figure 9-36). There is some evidence that noise-induced vertigo is due to direct stimulation of vibration-sensitive end organs in the vestibular apparatus. Nystagmus can be induced by noise of extreme intensities (over 150 dB) directed into the ears of deaf subjects (1). The vertigo and disorientation might result from irradiation of vestibular centers in the brain by the "overflow" of impulses from the intensely-stimulated auditory pathway. Feelings of rotation are not a feature of noise-induced vertigo (40).

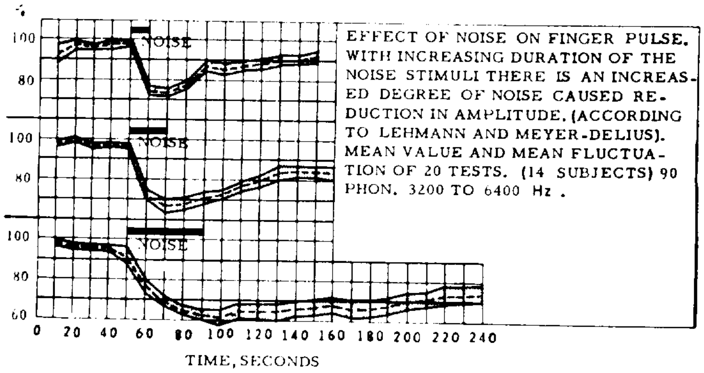
Apart from subjective effects and interference with performance and communication, intense noise elicits certain central neurophysiological reactions. Very loud or sudden noises evoke fear and avoidance reactions in man and animals. Continuous loud jet noise (overall levels of 120 dB to 7,500 Hz) can produce irritability and a sense of fatigue (50, 101), the neurophysiological basis of which is difficult to define. Experimental evidence exists, however, to show that, in addition to the direct sensory projection to the auditory cortex, the labyrinth projects to the reticular activating system of the brain stem, where an increase in activity is produced by intense acoustical stimulation (199).

Loud tonal signals produce arousal and have the effects of blocking alpha activity in the electroencephalogram and evoking on-and-off responses and auditory driving at 10 Hz (157). It is, of course, commonplace that noise awakens sleepers. It is most likely to do so during the early stages, before the sleep is deep (108). In certain animals (notably rats, mice, and other rodents), intense noise can induce epileptiform fits, or audiogenic seizures (6).

A variety of clinical and physiological indices have been observed to show changes in response to intense noise (50, 82). These changes include fluctuations in respiratory rate, pulse rate and blood pressure (101, 124, 125), decreases in gastro-intestinal motility (179) and alterations in regional blood flow, including that in the cochlea itself (163).

There are many investigations, primarily European, dealing with physiological effects of noise on the circulatory and endocrine systems (68). These workers report constriction of peripheral blood vessels in the skin as the most consistent characteristic reaction of the sympathetic nervous system to noise (101, 124, 125). This increase in peripheral vascular flow resistance is followed by a general decrease in arterial blood flow. The degree of this reaction depends on the intensity of the noise, is independent of the frequency, but increases with the bandwidth of the noise. These reactions were found to start at loudness levels between 60 and 70 phons and remained unchanged throughout the exposure. Therefore, they are considered phenomena separate from startle reactions. They are independent of the subject's familiarity with the noise since they were also found in industrial noise workers when exposed to the same noise spectrum in which they had worked for years. These reactions are also reported to be present, to an even stronger degree, during sleep.

The time for peripheral circulation to return to normal was, for exposure up to one hour, always longer than the exposure time. An example of such noise effects on the finger pulse and its recovery time is illustrated in Figure 9-35. That continuous or too frequent activation of this normal, primitive emergency reaction can lead to permanent changes and effects is only inferred in some studies. A clinical study of 1,000 steel workers revealed a statistically significant increase of vascular disorders and cardiac arrhythmias among groups exposed to high noise environments (90-120 phons) for more than three years (101). Even after exclusion of workers using pneumatic tools, symptoms similar to those in Raynaud's phenomenon were statistically more frequent among workers exposed to the highest noise level.



EFFECT OF NOISE ON FINGER PULSE. WITH INCREASING DURATION OF THE NOISE STIMULI THERE IS AN INCREASED DEGREE OF NOISE CAUSED REDUCTION IN AMPLITUDE. (ACCORDING TO LEHMANN AND MEYER-DELIUS). MEAN VALUE AND MEAN FLUCTUATION OF 20 TESTS. (14 SUBJECTS) 90 PHON. 3200 TO 6400 Hz .

Figure 9-35

Effect of Noise on Peripheral Circulation

(After von Gierke(68), adapted from Lehmann and Meyer-Dlius(124))

A battery of tests, including renal, electrocardiographic, electroencephalographic and haematological examinations have been performed on human subjects exposed to turbojet noise at an overal SPL of up to 120 dB (50). Their findings were largely negative and, although fluctuations in the fasting blood sugar level were recorded, the results of the experiments indicated complete physiological adaptation to the noise. In general, the non-aural physiological reactions to noise appear to be non-specific responses to startle, fear, or stress. Therefore, the metabolic and endocrinological effects of noise may generally be interpreted as non-specific responses to noise as a stress (82). A number of studies have been made of the adaptation response to noise, including measurements of blood eosinophil levels and adreno-cortical function (6, ,50, 83). Weight losses ranging from 5. 5 to 19 lbs in five out of nine human subjects exposed to jet noise for a total of 20 hr over a period of 6 weeks have been recorded (50). The causes of this weight loss are not entirely clear.

Effects of Noise on Performance

Effects of noise on nonauditory performance have been demonstrated 48, 79, 102, 103, 114, 138, 159, 163, 171). Work efficiency on tasks involving vigilance (alertness) over long time periods is reduced in noise environments of the order of 100 dB (48, 102). Levels of noise above 90 dB degrade performance of multiple-choice, serial-reaction tasks. High-pitched noise having a spectral preponderance above 2000 Hz had a more deleterious effect than low-pitched noise below 2000 Hz. Recently psychomotor performance using Atsai-Partington test of 16 subjects was evaluated under four noise conditions, during four test sessions. Three experimental conditions each began with different intensities of noise (quiet, overall 85 dB, or overall 95 dB) extending over a band from 150 to 9,600 Hz. After 30 minutes exposure the noise was changed to a final high intensity level (110 dB), which lasted for 15 minutes. The fourth condition served as a control, in which quiet prevailed throughout the entire 45 minute period. The results partially supported the hypothesis that greater changes in noise levels produce greater decrements in performance. There was, however, a strong interaction between noise conditions and sessions. The nature of this interaction indicated that this phenomenon does not occur uniformly throughout the course of learning, and probably is of lesser importance for well learned tasks.

Psychomotor performance has also been measured on a rail test during free-field exposure to wideband noise at an overall level of 120 dB. Subjects wore various combinations of ear protectors to obtain experimental conditions of: (1) sound pressure levels equal in both ear canals (balanced condition) and (2) sound pressure level greater in one ear canal than in the other (unbalanced condition). Man's ability to maintain his equilibrium was adversely affected by the unbalanced noise condition. Future research will be directed to performance in exposure conditions higher than those employed in this study.

It has been concluded that in tasks calling for both speed and skill, noise increases the incidence of mistakes although the rate of working may remain unchanged (82). It has also been shown that vigilance suffers in the presence of intense noise (overall SPL = 114 dB re 0.0002 µb). Time-judgment may also be altered by noise of a similar intensity in a complex manner (103,105). There is a possible connection between signal rate and the effects of noise in vigilance. Harmful effects of noise have been found on a task which involved a high signal rate coming from several sources of information, while no harmful effects of noise were found on a closely similar task with a low signal rate and only one source of information (103). It might well, however, have been division of attention rather than the presence of numerous signals, which made one of the tasks sensitive to noise, although doubt is shed on this hypothesis by a more recent study (19). In a task which always involved three sources of signals, it was shown that effects of noise were less likely to appear if note was taken only of those cases in which the subject was absolutely certain that he had seen the signal which his instructions required him to detect. If, however, note was taken of responses made with a low degree of confidence, effects of noise were more likely. This study in itself did not provide sufficient evidence to exclude altogether the role of division of attention. In a later experiment men were asked to watch a regularly flashing light and to report any flashes which were abnormally bright. Some subjects watched only one light and received a low frequency of signals; some subjects watched three lights, any one of which could deliver a signal, and each of which in fact delivered as many signals as the single light in the condition already described. A third group of subjects watched only one light but received as many signals as did the subjects who watched three lights. The clearest deterioration in performance in noise appeared in this latter group who did not have to divide attention but who did receive a high rate of signals. There was no sign of an effect upon the men who saw very few ignals, who were indeed, if anything, improved by a loud noise. The subjects lividing their attention between three sources of signals were in an intermediate condition.

The mechanism of the effect of noise is still ambiguous although the bove physiological and psychological measures suggest that it is indeed rousing. Response-time in a vigilance task is lengthened during combination of noise and vibration, and combined environmental stresses (heat, oise, vibration, etc.) may be synergistic in their effects on performance (129). n a recent study, ten pilots were tested for 20 minutes under ten combinations of heat and noise (39). The subjects simultaneously performed two nonitoring tasks and one tracking task. Data were also obtained on six hysiological measures and two subjective measures. The study indicates that emperatures as high as 110°F (in combination with 50 percent relative humidty and 150 feet per minute air velocity) and noise as high as 110 dB result in no degradation in performance or thermal equilibrium. Heat was found to increase heart rate, axillary temperature, and thigh temperature, but did not affect rectal temperature. Noise was found to increase heart rate and respiratory rate. Interaction between noise and heat suggests that noise lowered thigh temperature at ambient temperatures in the vicinity of 100°F. The subjective data indicate that 80°F is the most comfortable temperature at levels of humidity and air velocity that were used. The subjects were unable to estimate the effects of heat on their performance, although they were able to estimate the effects of noise.

In general, it may be said that the effect of intense noise on work is distracting rather than disabling, and noise is most troublesome when it is irrelevant to the task in hand. Extremely high noise levels can interfere with the accuracy of precision manual-dexterity tasks through noise-induced vibrations of body parts. They can affect the sense of equilibrium, add to disorientation, motion sickness, etc., depending on the specifics of the environment and the type of noise. It should be remembered that the level of noise required to exert a measurably degrading effect on task-performance (overall SPL greater than 90 dB) is considerably higher than the highest levels which are acceptable according to other criteria (e. g., hearing conservation or communication) (82).

The possible use of noise and variations in noise patterns as positive psychological stimuli to alleviate isolation and monotony has been studied (19, 210). The masking of pain by noise, as recently applied in dental work (audio analgesia), is also an effect to be mentioned in connection with space missions (64).

It is sometimes claimed by litigious farmers that aircraft noise so disturbs farm animals that chickens fail to lay, cows fail to yield milk, or pigs fail to fatten (209). Studies of the last phenomenon, supported by endocrinological investigations, yielded no evidence that the animals were adversely affected by repeated exposure to intense aircraft fly-over noise (209).

Low Frequency and Infra-audible Sound

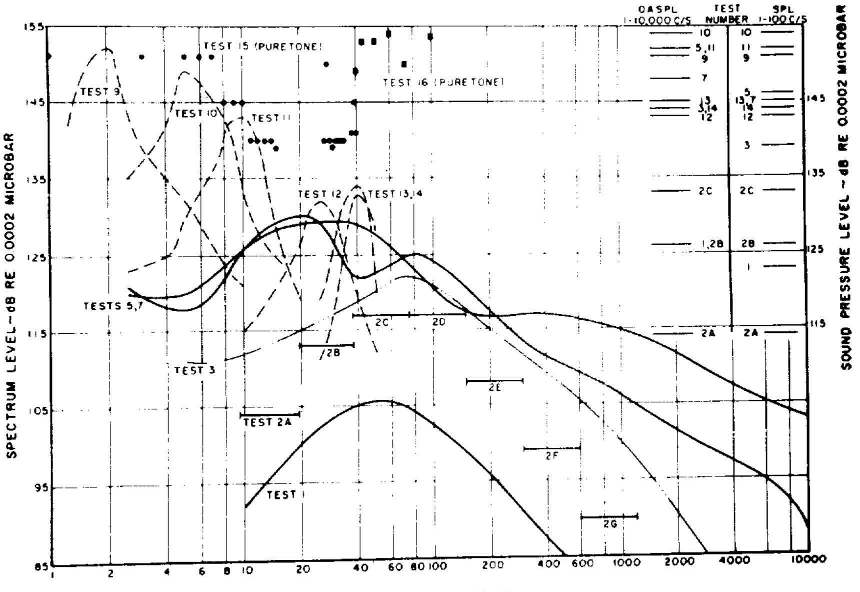
Exposure to low-frequency, high-intensity noise has had little study prior to the space program (9, 70). Pain thresholds were recorded at approximately 179 dB for static pressure, 165 dB at 3 Hz, and decreasing to the range of 140 dB from 15 to well above 100 Hz. In the past, little comment was made on nonauditory effects. The noise-experienced subjects of the previous studies observed no sensations of disturbed equilibrium or nausea during exposures to tones below 30 Hz even at sound pressure levels inducing pain (9).

Recent studies cover the spectra noted in Figure 9-36a (138). For the sake of comparison, random noise exposures are plotted as spectrum level. Overall sound pressure levels and levels for the 1-100 Hz frequency range are indicated on the right ordinate. Five noise-experienced Air Force officers (4 males, 1 female, ages 24 to 26) comprised the subject panel for these tests. For exposure to the jet engine noise (test 3) heavy clothing was worn because of low ambient temperature; for the other tests, light clothing was worn. Standard Air Force ear protectors (earplugs, earmuffs or the two combined) were worn throughout the exposures to the jet engine (test 3), to the Thermal Structures Tunnel (tests 4-8) and to the RTD Low Frequency Siren (test series 16) because the sound pressure levels for the frequency

Figure 9-36

Response to High Intensity - Low Frequency Noise

(After Mohr et al[138])



a. Summary of Test Environments

Summary analysis of representative noise exposures for tests 1 to 16 Random noise exposures are plotted in spectrum level (left ordinate) with overall sound pressure levels indicated on right ordinate. Response to these spectra are given in Table 9-36b.

Figure 9-36 (continued)

b Table of Physiological and Performance Responses to Spectra of Figure a

Test 1 - At sound levels predicted for the crew compartment atop the Saturn Booster, subjects reported no significant disturbance of vision, verbal communication, spatial orientation or finger dexterity. Pulse rates remained stable with no significant fluctuations that could be ascribed to the noise exposure. Minor chest wall and body hair vibration were noted but were in no way considered distressing. All subjects concurred that the exposure was unquestionably tolerable.

Test 2 - Test was carried out in seven steps, during each of which the subjects were exposed for two minutes to a single octave band of white noise at a sound pressure level approximately 10 dB higher than the levels for the corresponding bands in the test 1 spectrum. All subjects reported the test environments as tolerable with no significant subjective responses other than mild chest wall and body hair vibration noted during the 35-70 Hz and 70-140 Hz band exposures. Objective observations were negative. Subjects' speech signals were being modulated somewhat by the noise, though intelligibility remained good. It was clear from the experiences of all subjects during these exposures that insert earplugs do provide substantial attenuation for noise of very low frequency. It was equally clear that none of the earmuff devices when worn alone gave significant reductions and that some models appeared to amplify the noise under the muff. Earmuffs placed over insert earplugs did seem to add to the attenuation achieved by plugs alone.

One subject wore no ear protection for considerable of the total exposure time in tests 1 and 2 and each of the others tried the various noise environments without protection for short intervals. It is assumed also that minimal or no protection was afforded when muffs only were worn. No shifts in auditory acuity were detected following the tests.

Test 3 - All subjects considered the noise environment as tolerable so long as ear protection was used. Visual acuity, spatial orientation and hand coordination were not subjectively affected. However, all subjects reported mild chest wall vibration and one subject reported "awareness" of his respiratory action. Speech sounds were completely masked by the higher frequency portion of the spectrum making direct verbal communication within the noise field impossible. Limited speech communications is carried out by maintenance men in similar noise fields through use of interphone systems incorporating noise-cancelling microphones.

Tests 4 & 5 - Test 4 was unremarkable. The test 5 environment contained the highest levels of low frequency noise to which the subject panel had yet been exposed, but also contained very high level energy throughout the audible spectrum. The speech signals recorded were completely masked despite the noise reduction provided by microphone and shield. Pulse rates were increased 10 to 40 percent over resting levels. Two subjects reported mild chest wall vibration, two others noted mild nasal cavity vibration, and one of these perceptible throat fullness. All agreed that the addition of the high level infrasound did not appear to modify the responses observed many times previously in noise fields having similar energy distribution through the higher frequency ranges.

Tests 6, 7 & 8 - These tests provided exposures which retained intense very low frequency noise components but had relatively less energy in the higher frequencies. All subjects considered the exposures tolerable for the short durations involved. Speech signals were completely masked, nevertheless, except those of one subject who was stationed inside a vehicle which afforded appreciable attenuation of the high frequencies. His speech was definitely modulated but the poor intelligibility achieved was attributed to the masking. All subjects reported mild to moderate chest wall vibration; two subjects noted throat pressure; three subjects experienced perceptible though tolerable interference with the normal respiratory rhythm. Pulse rates measured during test 7 exhibited no significant changes during the exposure.

Throughout these tests visual acuity, hand coordination and spatial orientation were subjectively normal.

Tests 9 - 11 - The most prominent effects attributable to the infrasonic noise spectra (test 9-11) occurred during exposures without ear protection. An uncomfortable sensation reflecting pressure build-up in the middle ear was elicited which required frequent Valsalva to relieve. This effect was almost entirely absent when insert earplugs were used. Although earmuffs alone proved no more effective in attenuating the low frequency noise than they had in tests 1 and 2, they did help prevent the middle ear pressure changes. Three subjects described an occasional tympanic membrane tickle sensation during these exposures without protection and one subject observed marked nostril vibration. Another noted mild abdominal wall vibration during exposure to the test 10 spectrum (5-10 Hz). No shifts in hearing threshold were detectable one hour following these exposures. When ear protectors were worn to lessen the middle ear pressure changes, exposures to infrasound of these levels were judged well within tolerance.

Tests 12-14 - The maximum intensity low sonic exposures produced moderate chest wall vibration, a sensation of hypopharyngeal fullness (gagging) and perceptible visual field vibration in all subjects. Two subjects experienced mild middle ear pain during brief periods without ear protection but a third had no sensation of tickle or pain. Recorded speech sounds exhibited audible modulation; however, the intelligibility scores were unchanged from the control values (control scores, 94-98 percent; exposure scores 93-98 percent). Post-exposure fatigue was generally present after a day of repeated testing. The exposures as a group were not considered pleasant; however, all subjects concurred that the environments experienced were within the tolerance range. No statistically significant objective effects were detected in tests 9-14, but the objective tests must be considered gross and would not necessarily detect minor decrements occurring below the threshold of subjective recognition.

Test 15 - Exposures to 24 discrete frequency noise fields showed both objective and subjective responses qualitatively similar to those elicited by the corresponding narrow band spectra. Pressure build-up in the middle ear was not a factor at 30 Hz and above but the gag sensation was magnified for at least one subject. Although all exposures were judged tolerable, it was noted that the subjective sensations rose to intensity very rapidly as sound pressure levels were increased above 145 dB.

Test 16 - Siren capability limited the maximum levels of exposure at 40 Hz and 43 Hz. Above this frequency range voluntary tolerance of the three subjects was reached at 50 Hz (153 dB), 60 Hz (154 dB), 73 Hz (150 dB), and 100 Hz (153 dB). The decision to stop exposures at these levels for the time being was based on the following subjectively alarming responses: mild nausea, giddiness, subcostal discomfort, cutaneous flushing and tingling occurred at 100 Hz; coughing, severe substernal pressure, choking respiration, salivation, pain on swallowing, hypopharyngeal discomfort and giddiness were observed at 60 Hz and 73 Hz. One subject developed a transient headache at 50 Hz; another developed both headache and testicular aching during the 73 Hz exposure.

A significant visual acuity decrement (both subjective and objective) occurred for all subjects during the 43, 50, and 73 Hz exposures. Speech sounds were perceptibly modulated during all exposures; however, analysis of the speech tapes revealed no decrement in intelligibility that could be primarily ascribed to the modulation effect. Intelligibility scores fell from a normal 95-100 percent to a low of 77-86 percent for the highest level exposures; a decrease of this magnitude would be expected to occur, however, due to the masking effect of the higher harmonics present in the noise environments.

All subjects complained of marked post-exposure fatigue. No shifts in hearing threshold were measurable two minutes post exposure; the earplug and muff combinations worn are known to provide sufficient protection against the higher harmonics of the noise fields and were apparently effective to an appreciable degree in attenuating the fundamental tones. Recovery from most of the symptoms was complete upon cessation of the noise. One subject continued to cough for 20 minutes, and one retained some cutaneous flushing for approximately four hours post exposure. Fatigue was resolved by a night's sleep.

range known to injure the organ of hearing were also very high. During exposures in the AMRL High Intensity Noise Chamber (tests 1-2) and in the NASA-LRC Low Frequency Noise Facility (tests 9-15), where the higher frequency components were relatively low in level, most subjects experimented with various combinations of protection as well as exposure with bare ears.

Although exposure times of at least two minutes each were desired, the period for test 3 (jet engine) was limited to one minute by ground operating restrictions on the engine. Durations of exposures to the Thermal Structures Tunnel noise (4-8) were determined by the blow-down time of the tunnel under the conditions used. For tests 4 and 5, exposure time was 60 seconds; for tests 6-8, durations were only 25 seconds. All other tests lasted a minimum of two minutes at each intensity level presented.

The following tests were performed: visual acuity (modified Snellen E); one-leg stand; finger to nose test; handwriting; finger dexterity; hand coordination; direct speech intelligibility; and objective intelligibility by a modified Rhyme Test of Word Intelligibility, scored by trained listeners using the subjects speech responses recorded on magnetic tape through noise-canceling microphones encased in acoustically isolated shields. The test results noted in Table 9-36b are taken directly from the report (138).

In summary, the maximum infrasonic exposure levels produced by the available simulation devices did not reach the voluntary tolerance limit for noise-experienced subjects; however, the unusual sensations excited by the oscillating pressure environment could be alarming to the naive observer. In the very low sonic frequency range, chest wall vibration, gag sensations, and respiratory rhythm changes were regularly observed. But the limits of voluntary tolerance were not exceeded by the exposure levels available from the various devices.

In the 50-100 Hz range, the simulator capability for discrete-frequency noise was sufficient to generate subjectively intolerable environments. Responses including headaches, choking, coughing, visual blurring, and fatigue were sufficiently alarming to preclude undergoing higher level exposures without more precise control of the noise environment and definition of the physiologic effects elicited.

The presently available data thus support the conclusion that noise-experienced human subjects, wearing ear protectors (145), can safely tolerate broad-band and discrete frequency noise in the 1-100 Hz range for short durations at sound pressure levels as high as 150 dB (138). At least for the frequency range above 40 Hz, however, such exposures are undoubtedly approaching the limiting range of subjective voluntary tolerance and of reliable performance. As would be expected, the responses reported by these five subjects during the various test series reflect considerable variability in the subjective effects. At present, the magnitude of possible individual and group variability cannot be accurately estimated.

Sonic Booms

Sonic booms are one form of noise which is of great current interest because of the potentially large percentage of the population affected by it and because of economic consequences (7, 16, 18, 23, 93, 131, 132, 144, 181). None of the response criteria discussed can be meaningfully applied to its evaluation. Disregarding the brief startle response, no damage to hearing or any other harmful physiological effect can be attributed to exposure to pressure waves of the magnitude experienced by communities. As shown in Table 9-37 there is hardly any noteworthy interference with most tasks or job proficiences. In this area, tools are restricted to measuring the diffuse annoyance or complaint pattern of the population exposed to the boom and to arriving at operational criteria based on such data. This is the goal and purpose of the various sonic boom studies conducted by the US Air Force, NASA, and the FAA over the last ten years on an ever-increasing scale. These are not medical safety criteria, not task interference criteria, but expressions of the majority of a population showing that they are annoyed and willing to complain and act against such noise intrusion into their personal lives (68).

Table 9-37

Measured or Predicted Effects of Overpressure from Supersonic Vehicles (Sonic Boom)

(After von Gierke(68), adapted from Nixon(144))

Peak Overpressure			Predicted and/or Measured Effects	
Lbs/In²	Lbs/Ft²	Dynes/cm²		
$0-7.10^{-3}$	0--1	0—478		No damage to ground structures. No significant public reaction, day or night.
$7 \times 10^{-3}-1.05 \times 10^{-2}$	1.0--1.5	478—717	Sonic booms from normal operational altitudes:	No damage to ground structures; probable public reaction.
$1.05 \times 10^{-2}-1.4 \times 10^{-2}$	1.5--2	717—957	Typical community exposures (seldom above 2 lbs/ft²)	No damage to ground structures; significant public reaction, particularly at night.
$1.4 \times 10^{-2}-3.5 \times 10^{-2}$	2.0—5.0	957—2,393		Incipient damage to structures.
$1.4 \times 10^{-1}-8.10^{-1}$	20—120	$9.57 \times 10^{3}-5.74 \times 10^{4}$	Measured sonic booms from aircraft flying supersonic speeds at minimum altitude: experienced by humans without injury.	
5	720	3.44×10^{5}	Estimated threshold for eardrum rupture (maximum overpressure),	
15	2,160	1.033×10^{6}	Estimated threshold for lung damage (maximum overpressure),	

Ultrasound

The mechanics of the absorption of ultrasonic vibrations by body tissues have been covered in Vibration (No. 8). (See Figure 8-19). Data on the general acoustic properties of different human and animal tissues are also available (41, 77, 80).

Ultrasound has not been studied as a naturally occurring phenomenon (except for low-frequency, low-intensity emanations of animal origin) (20).

Information has been obtained in laboratory environments and almost entirely in animal rather than human experiments (42, 88). The most comprehensive investigations, with detailed histological studies, have been made on the central nervous system of the cat and other small animals (42, 60). The human brain has been modified at localized sites by intense ultrasound, but there has been insufficient material for extensive histological study (61). However, the dosage conditions employed to induce functional change, and the histological results available, indicate that the effects on the human brain are the same as those observed in the cat. Precisely placed ultrasonic lesions have been produced in a number of deep brain structures in man for treatment and relief of the signs and sensations associated with hyperkinetic, hypertonic, and intractable pain disorders (61, 62, 77, 134).

High-intensity ultrasound produces physiological changes which are observable immediately (60), but the effects of tissue structure, at dosages which produce selective irreversible changes, occur at sub-microscopic sites and cannot be seen in stained tissue sections until after a time interval of minutes to an hour after exposure. Acoustically induced cavitation has been eliminated as a primary factor in the development of irreversible changes, by producing lesions as well as motor deficits under a hydrostatic pressure sufficiently great to prevent tension forces from occurring in tissue. The fact that physiological changes are evident immediately after exposure, but that histological changes do not begin to appear until later, has led to investigations of the possible interaction of intense noncavitating ultrasound and biologically important molecular species in solution (78, 88, 91).

Damage from ultrasound in the space program may arise in exposure to rocket and jet noise. Ultrasonic vibrations are also used in non-destructive testing of metals, in cleaning baths, in measuring devices, in power and communication control, in drilling and welding processes, and in medical diagnosis (77, 80, 88, 168).

The effect of diffuse total body ultrasonic exposure from jet engines and other sources has been reviewed (195). Spectral analyses of the noise obtained near turbo-jet engines on the ground or aircraft in flight show that both sonic and ultrasonic vibrations are produced. Intensity levels appear to be reduced as engine speed decreases. There is evidence that, with increasing air speed, the overall intensity level of the noise increases and strong energy components may appear at ultrasonic frequencies as well as in the audible range. This tendency is exaggerated as the speed approaches a Mach number of 1.0. The effects upon man are alleged to involve nausea, disturbance of equilibrium, fatigue, mental confusion, headache, and auditory, visual, and motor disturbances. The effects are said to be transient. Disturbances of equilibration, fatigue, and confusion are the most frequently reported symptoms. These deleterious effects are attributed to ultrasonic vibrations. The logic by which ultrasonic vibrations become the cause is unclear in many of the reports and causal relationships have not been established. To date, such reports have not been based on systematic experimentation (78, 195). Clothing variables are a major factor not under control in the epidemiological studies. Response of animals to total body exposure cannot be directly extrapolated to man (78, 173). In animals, changes in the hematopoetic, endocrine, and nervous system have been noted at levels as low as 95-100 dB at 54 kc for 1-3 hrs (78).

Warm skin sensation and bone pain from overheating of the periosteum appear to be the first local symptoms noted at high exposures (173). Energy fluxes of over 0.1 watts/cm^2 for over 10 minutes are probably required for local tissue damage (127, 173). The energies involved in the pulsed diagnostic technique vary from 0.004 to 0.04 watts/cm^2. At these levels no tissue damage has been observed (5, 58). When ultrasound has been used to produce tissue damage in therapeutic studies, the levels have ranged from 3 to 100 watts/cm^2 at a duration up to ten minutes (167). In these studies, there appears to be an outstanding deficiency in reporting how the energy levels of watts/cm^2 were determined. At present, there is no method available for determining this for pulsed waves; and only relative methods for continuous waves. In fact, only in the past years has it been possible to ascertain the electrical-physical continuity of ultrasonic transducers (130). The only way at present to express an energy value of any merit is to determine the energy in the electrical pulse to the transducer and multiply it by the measured, direct-energy conversion efficiency of the crystal; then divide by the area of the crystal. Caution must therefore be used in evaluating the older literature.

NOISE CONTROL AND PROTECTION

There now exists a substantial body of theoretical and technical knowledge about noise and its control (12, 85, 212). In order to reduce the harmful effects of noise, the first step must be to decide what are to be the criteria of acceptable noise exposure - that is to say, which effects of noise are to be protected against and how much noise control is necessary. The second step is to analyze and measure the offending noise, using the techniques already outlined or, when advance planning against noise is contemplated, to predict the acoustical power of the source or sources, the probable quality of the noise produced and its routes of propagation. From the information obtained in the first two steps, it is then possible to calculate the amount of noise reduction required. The final step is to select and apply the most appropriate and economical means of noise control. There are three principal ways in which noise may be attacked: by reduction at source, by reduction in the transmission pathway from the source to man, and by reduction of the effects produced by noise on man.

A number of attempts have been made over the past twenty years or so to specify the maximum levels and durations of various types of sounds that persons can tolerate without suffering some degree of permanent hearing loss. These specifications have usually been in the form of graphs or contours showing, as a function of either the frequency spectrum or the duration, the sound pressure levels considered tolerable. These contours often have been labeled "damage risk criteria," although strictly speaking the contours are not "criteria" - the criterion is the degree of permanent hearing loss in a given percentage of the exposed people that the person deriving the contours deems reasonable. It has been suggested that these be called "damage risk contours" (DRC's) and not damage risk criteria (112).

In the past, the criteria against which damage risk contours were drawn were not usually precisely stated. This was dictated primarily, of course, by the general lack of data available as to the precise effects of exposure to intense sound on hearing. In assessing human reactions to environmental stimuli as a basis for exposure criteria, it must be kept in mind that such reactions can be of completely different natures. For clarity these categories should be separated. Perhaps the best classification is by methods of measurement used; these are (a) objective physiological responses; (b) efficiency of job performance; and (c) subjective verbal response to stimuli. Each of these reactions can lead to different criteria. At question also is what percent of the population at risk should be protected against these criteria. Efforts are underway to arrive at international agreement on noise control and risk criteria in many different environments. (100, 155)

Noise Reduction

In the past, criteria for the prevention of permanent hearing loss took the following form (47, 71, 72, 112, 177, 192, 194). In setting limits for continuous daily exposure, it was assumed that the ears were unprotected and exposed continuously during normal work hours over a period of 25 years (177, 192). The limits for such exposure to broadband noise were approximately 85 dB in the octave bands 300-600, 600-1200, 1200-2400, and 2400-4800 Hz. For higher octave-band sound pressure levels, ear protection was recommended. For octave band sound pressure levels in excess of 95 dB, ear protection was considered mandatory. As noted above, the ear cannot tolerate pure tone (or discrete frequency) levels for as long an interval as broadband noise, so these limits were usually lowered by 10 dB, if the noise contained predominant narrow band components. The permissible sound pressure levels in the octave bands below 300 Hz were somewhat higher. Some criteria assumed that the contribution of noise in these frequency bands to hearing impairment was negligible. Other damage risk criteria made allowances for the natural loss of hearing acuity with age (presbycusis) and allowed, for example, instead of an average 85 dB for the octave bands 300 to 4800 Hz, levels of 92 dB for persons younger than 30 years and 80 dB for persons between 50 and 60 years old (111).

When the exposure was less than 8 hours, daily exposure to higher levels than those specified could be tolerated. The assumptions made were either that equal quantities of acoustic energy determined by constant product (exposure time x square of sound pressure (47) or equal quantities of the product (exposure time x sound pressure (111) were equally injurious to the ear. The "constant energy concept" is in widespread use but is probably on the conservative side. The results of studies relating temporary hearing loss to exposure time were in favor of the "constant exposure time x pressure concept (180, 202). Using either one of these concepts, maximum exposures "equal" to the 8-hour, damage-risk contours discussed above were allowed. These short-time contours are illustrated in Figure 9-38. If several significant exposures at various intensities took place during a working day, these exposures were converted into "equivalent exposure time" (EET) for the criterion level for an 8-hour exposure. If all the equivalent exposure times when added together, exceeded 480 minutes at the 8 hour criterion level, the daily exposure limit was exceeded (111, 192).

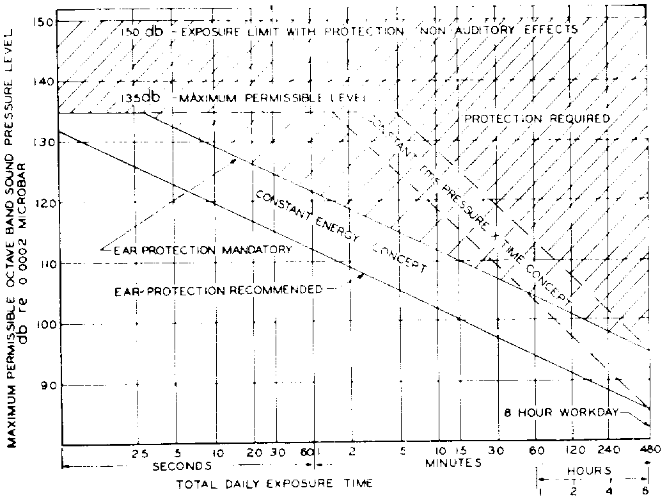


Figure 9-38

Damage Risk Contours for Short Term Exposure to Broad-Band Noise

The curves based on the "constant energy concept" and the "constant pressure times time concept, are shown. The curves designate the limits for safe daily exposure over a period of many years in terms of maximum permissible exposure time or sound pressure level in the octave bands of 300-600, 600-1200, 1200-2400, and 2400-4800 Hz. (For exposure to pure tone noise, the curves should be lowered by 10 dB, however, the maximum permissible level of 135 dB stays the same.

(After von Gierke and Hiatt[(71)])

As more and more data on the hearing of persons exposed to intense sound have become available, a simpler and more significant concept has emerged on which meaningful criteria of the risk involved in exposure to sound can be based. These are as follows (112, 139):

- For a given population of people exposed to a given intense sound, some will suffer more hearing loss than others. In general, the damage risk contours developed in the past have been such that at least 50 percent of the people exposed to the so-called tolerable DRC's have suffered a significant permanent hearing loss.
- Practically speaking, courts of law, guided by otologists, have distinguished between hearing impairment and hearing handicap. By impairment is usually meant damage or a decrease in the ability of the auditory system to function normally, whereas handicap refers to the condition in which the impairment reaches the stage that the person, as a total organism, is not able to function normally in his everyday living. What is "normal" and what is a "handicap" are obviously subject to various interpretations, depending on value judgments of those attempting to define these terms.
- The only hearing handicap that is judged (according to most medical recommendations concerning industrial deafness) to be truly harmful to a person, and therefore possibly compensable according to law, is a hearing handicap for speech (128). "Impairment" is used by the AAOO and AMA as meaning a range from beginning to total disability to hear everyday speech in sentence form. Amount of impairment is given in percent based on binaural hearing determined by a

formula devised by the Committee on Conservation of Hearing and now accepted by most authorities and compensation commissions.

Specifying a damage risk criterion in terms of the statistical nature of hearing losses and in terms of some specified handicap for understanding speech should be a straight-forward process, even though controlled by the value judgments of those making the specifications. Perhaps more difficult, at least in a technical or scientific sense, is the problem of drawing the damage risk contours that are deemed to be acceptable according to whatever criterion one chooses. This task is made complex and difficult because of the tremendous variety of spectral and temporal patterns of sound to which people may be exposed. Sufficient data are available to undertake this task only on so-called "steady-state" sounds; the effects on hearing of that class of sounds called "impulse" have not been studied enough to permit much to be said about what types of exposures are to be considered tolerable (95, 96).

An attempt has been made to describe and explain a set of damage risk contours for steady-state noise that are drawn to meet a criterion based on the concepts outlined above and on the basis of a joint consideration of data of temporary and permanent hearing loss, or threshold shifts, due to exposure to sound (112). These make use of the concepts of speech intelligibility and noise masking covered above. In brief, the suggestion is made that speech energy is to be found between 100 and 6000 Hz or so, but it is maximal in the frequency region below 1000 Hz. It has been found that the speech frequencies below about 1700 Hz are equally as important to the intelligibility of speech as the frequencies above that level. For speech in sentence form, the lower range is more important. For this reason, it is appropriate to protect the ear more with respect to lower frequencies, below, say, 2000 Hz than at the higher.

The sounds in the conversational speech of a single talker cover a range of intensities of over 30 dB. Typically, the weakest components in speech uttered at conversational level and perceived 3 or 4 feet from the talker will be 10 to 15 dB or so above the normal threshold of hearing.

These considerations provide at least a partial basis for explaining the recommendation that the handicap for hearing speech starts only when hearing loss found at 500, 1000, and 2000 Hz averages 15 dB (128). Although this so-called 15 dB audiometric "fence" for evaluating handicap for speech is open to experimental question, it is generally accepted by medical experts at the present time (116). The value of such an approach is now under study by several groups (100, 128, 139).

Figures 9-39 to 9-49 are examples of the more recent approach to long- and short-term exposures (75, 115, 139). These have been accepted by the CHABA Working Group No. 46. Although the damage risk contours presented in these following figures are in terms of pure tones or one-third and full octave bands of noise, these figures are to be used in the evaluation of noises that have greater bandwidths, i. e., extend over more than one octave. The level of each one-third or full octave band in a broader band noise of a specified duration is to be compared to the damage risk contours given in the figures which follow.

If any single band exceeds the damage risk contours specified, the noise can be considered as potentially unsafe. As progressively more one-third or octave bands of a broader band noise reach the damage risk contours, the hearing loss will become extended over a wider and wider range of the sound frequencies to which the ear is sensitive. Nevertheless, hearing loss at any one frequency region should not be significantly greater than that expected from exposure to a band of noise located about one-half octave below that particular frequency region (115).

Using Figures 9-39 and 9-40, one can find either maximum sound pressure levels for given durations or maximum once-per-day durations for given sound pressure levels for the octave and one-third octave or narrower bands of noise indicated. Figure 9-41 presents damage risk contours for pure tones only. Figures 9-39, 9-40, and 9-41, for single exposures, apply not only to noises whose level is constant over the exposure period, but also to those with a fluctuating level, provided that (a) the noise does not remain at a single level more than 2 min, and (b) the level never drops below the 480 min curves on Figures 9-40 and 9-41, i. e., the level that can be tolerated for a full workday. The effective level of such a varying noise is equal to the average sound pressure level (SPL) of the noise over the exposure period. Several examples are given:

> Example: The level of a noise whose maximum energy is in the 1200-2400 Hz octave band varies between 90 and 100 dB, 30 second (sec) bursts of 110 dB alternating with 90 sec intervals of 90 dB. The effective level is, therefore,
>
> (30 sec x 110 dB + 90 sec x 90 dB)/(30 sec + 90 sec) = 95 dB SPL.

From Figure 9-40, the maximum tolerable exposure to this noise is seen to be about 35 min.

> Example: A generator with a pronounced whine at 1000 Hz varies in output level between 100 and 120 dB. Measurement shows that the time distribution of the levels is as follows: 120 dB, 25 percent of the time, 110 dB 40 percent, and 100 dB 35 percent. The average level is, therefore, 120 x 0. 25 + 100 x 0. 40 + 100 x 0. 35 = 109 dB. Figure 9-41 indicates that the maximum tolerable exposure to this whine is about 5 min.

Figures 9-42 through 9-49 provide functions showing damage risk contours for interrupted exposures to bands of noise. Figures 9-42 to 9-45 are used for the appropriate band limits or band center frequencies to show the maximum tolerable sound pressure levels for bands of noise having certain center frequencies or to show the maximum duration of daily exposure for bands of noise having certain center frequencies and known sound pressure levels and known on-fraction. The use of Figures 9-42 to 9-45 is limited to situations in which (a) there is alternation between noise and effective quiet

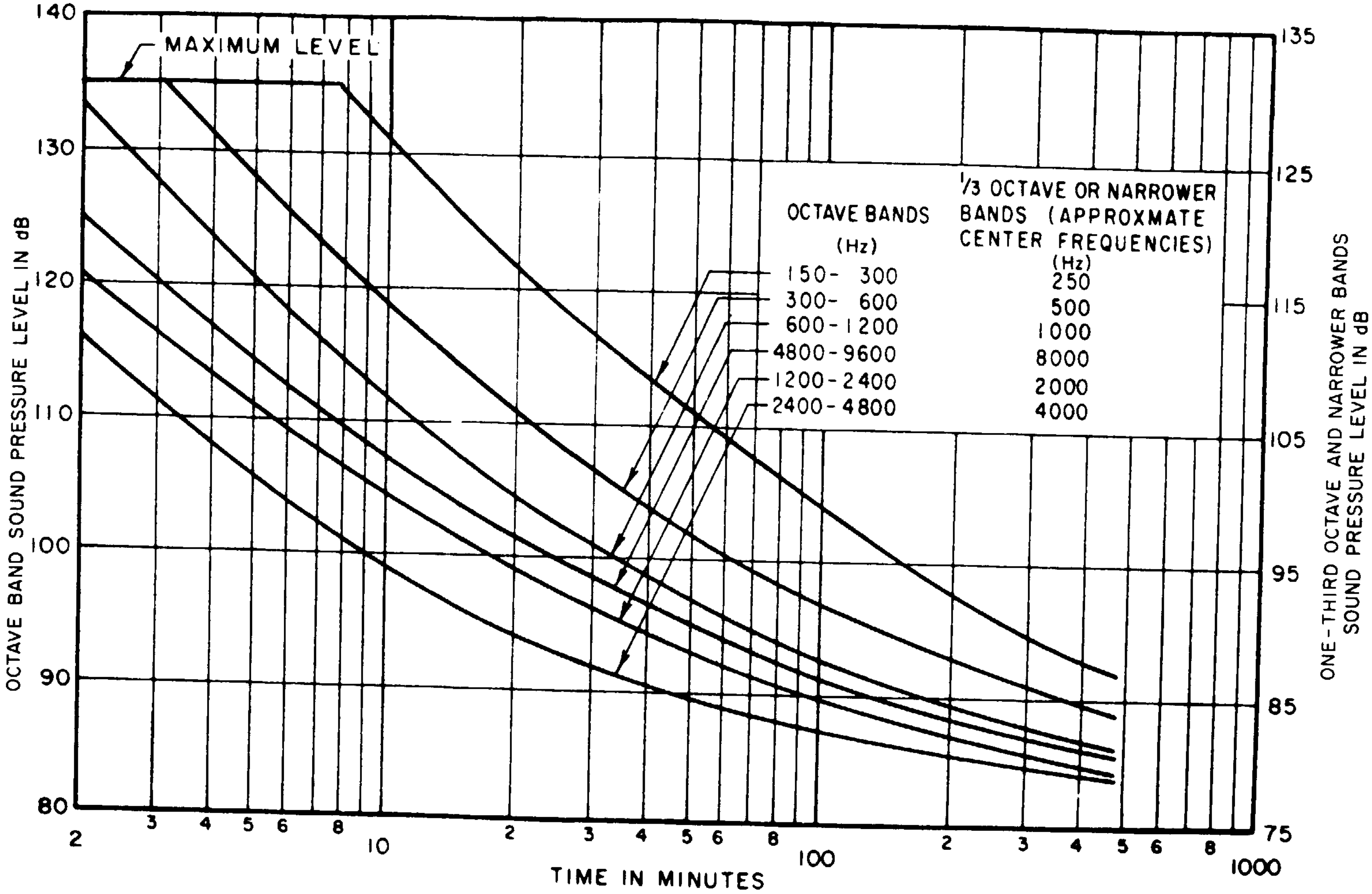


Figure 9-39

Damage Risk Contours for One Exposure Per Day to Certain Octave (left-hand ordinate) and Certain One-Third Octave or Narrower (right-hand ordinate) Bands of Noise

This graph can be applied to individual band levels present in broad band noise

(After Kryter - CHABA[139])

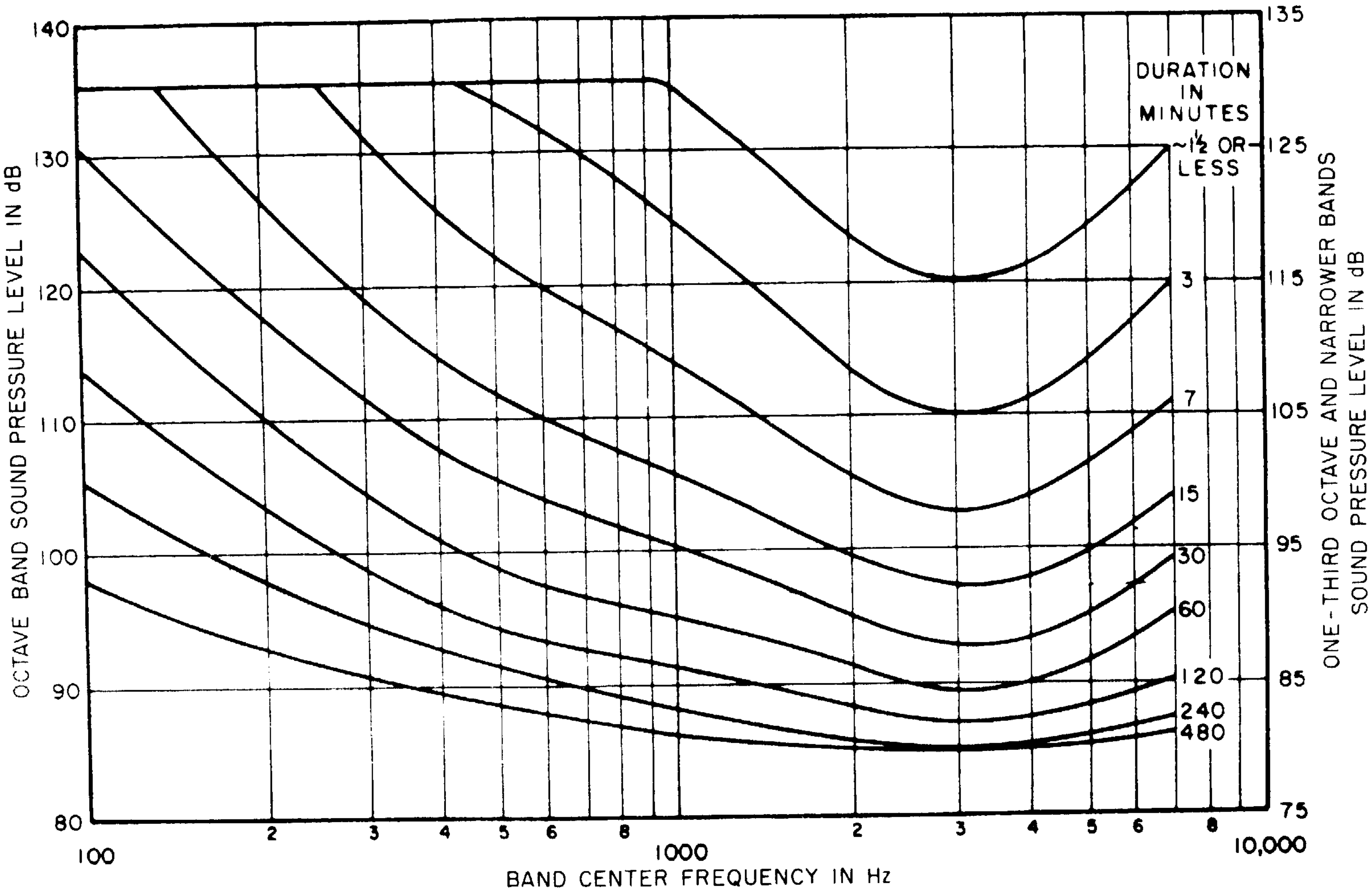


Figure 9-40

Damage Risk Contours for One Exposure Per Day to Octave (left-hand ordinate) and One-Third Octave or Narrower (right-hand ordinate) Bands of Noise

This graph can be applied to individual band levels present in broad band noise.

(After Kryter - CHABA$^{(139)}$)

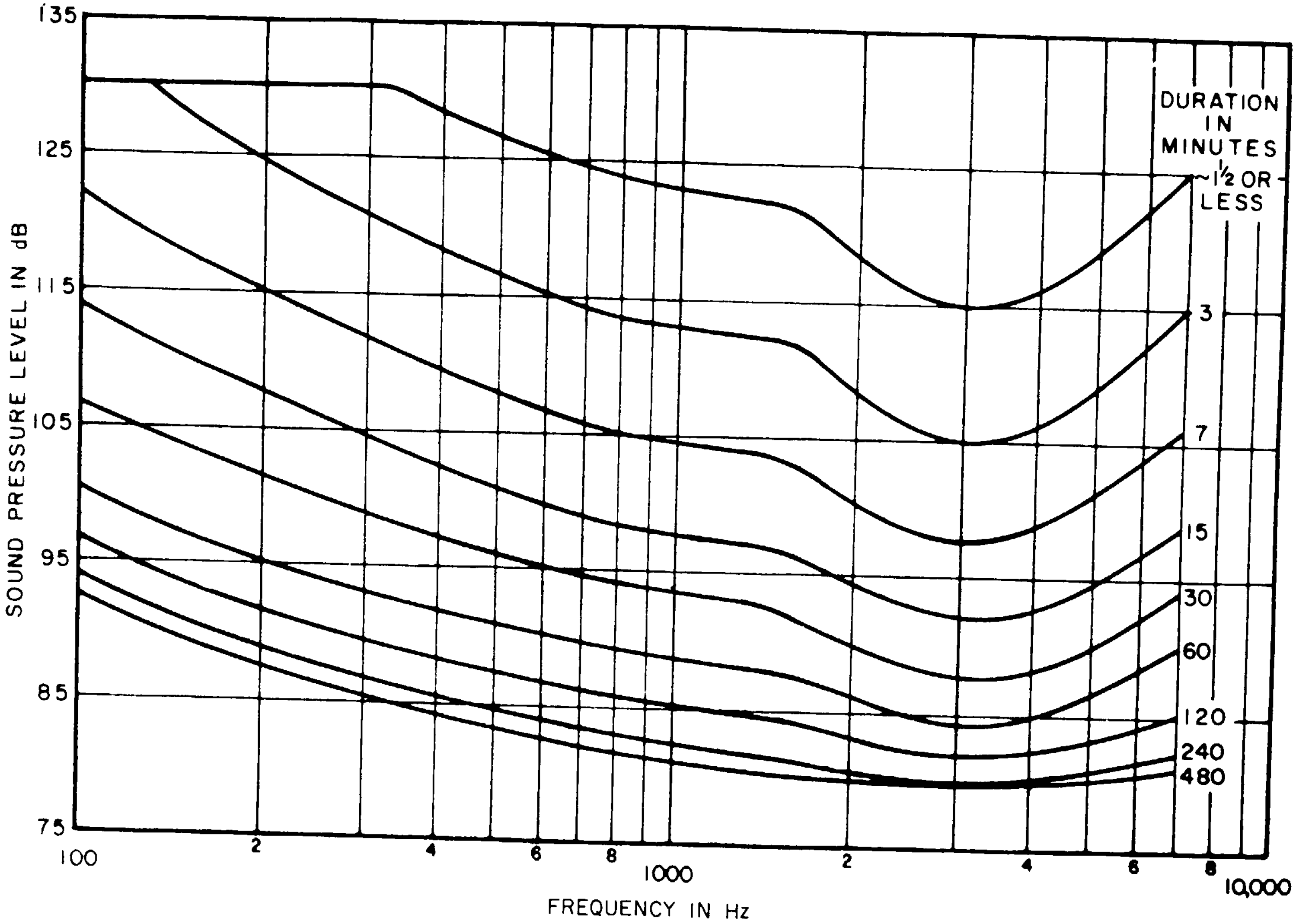


Figure 9-41

Damage Risk Contours for One Exposure Per Day to Pure Tones

(After Kryter - CHABA(139))

throughout the duration of daily exposure, and (b) individual noise bursts do not exceed 2 min in duration. "Effective quiet" exists when the noise level drops below the 480 min curves of Figures 9-40 and 9-41; the "duration of daily exposure" consists of the sum of the durations of the noise bursts and the effective quiet. "On-fraction" (the parameter of Figures 9-42 to 9-45) is the ratio of noise burst duration to duration of daily exposure; thus, it is not the ratio of noise time to quiet time, but the noise time divided by the noise-time-plus-quiet-time.

> Example: The maximum tolerable level of the 300-600 Hz octave band of noise that is on for 1 min periods followed by 1 min periods of relative quiet (an on-fraction of 0.5) and a total period of exposure that continues for 60 min is found by entering Figure 9-42 on the vertical line for 60 min. This line crosses the curve for an on-fraction of 0.5 at a sound pressure level of approximately 127 dB (left-hand ordinate of Figure 9-42), the maximum tolerable level for the 300-600 Hz octave band, during the "on" period. The maximum tolerable level in a 300-600 Hz octave band of noise would be 89 dB during the "off" period in this case.

Figures 9-46, 9-47, 9-48, and 9-49 may be used to show the interval of effective quiet that must follow an exposure to an octave band or one-third octave or narrower band of noise having a specified sound pressure level and duration, before the exposure can be repeated during the work day. Effective quite, again, exists whenever the noise level drops below the contour in Figure 9-40 for 480 min. These figures are to be used when the noise bursts are longer than 2 min in duration.

> Example: A 300-600 Hz octave band of noise (Figure 9-46) having a sound pressure level of 115 dB (fourth contour from the left, as indicated by the top row of numbers on Figure 9-46), and a duration of 10 min would require 45 min of effective quiet following the noise burst before a person could be exposed again to the noise, throughout the 480 min work day. Thus, an individual could be exposed eight or nine times to this 10 min noise during the work day, provided he was given a 45 min rest between each exposure.

> Example: A one-third octave band of noise with a center frequency of 2000 Hz displays the following time course. For 10 min the noise level alternates regularly between 90 and 100 dB, then drops to 70 dB (effective quiet) for 30 min. The effective level of the noise during the 10 min is thus 95 dB; Figure 9-48 indicates that a 10 min exposure to 95 dB (third contour from the left, indicated by the second row of numbers at the top of Figure 9-48), need be followed by only about 16 min of effective quiet. Therefore, the observed pattern (10 min noise, 30 min quiet) is tolerable over the 8 hr work day.

> Example: A noise having its maximum energy in the octave band 2400-4800 Hz has an effective level of 100 dB and must be on for 10 min. The intersection of the 100 dB octave band contour in Figure 9-49 and the 10 min burst duration (abscissa) cannot be

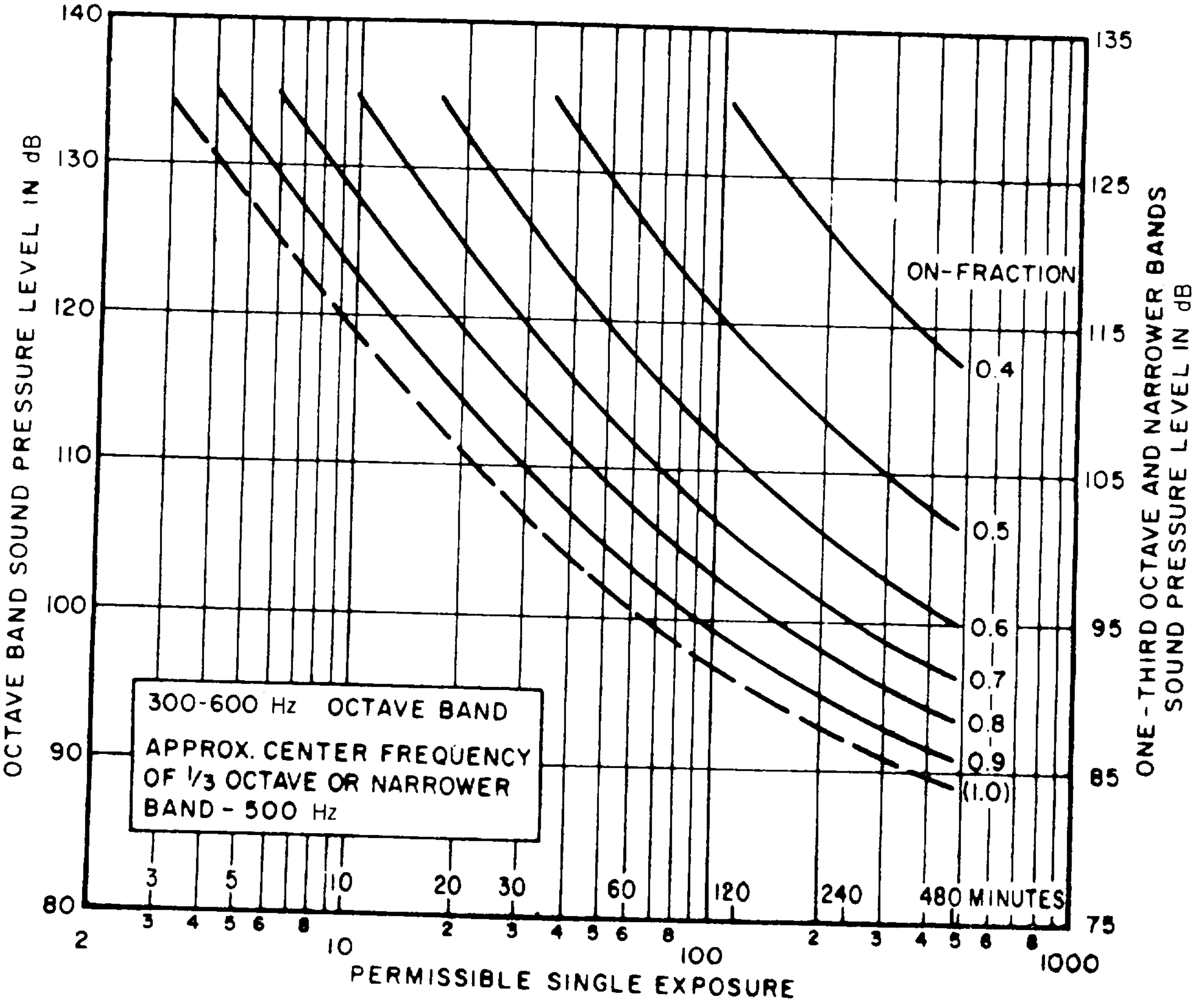


Figure 9-42

Damage Risk Contours for Short-Burst-Duration Intermittent Noise
(Noise bursts 2 minutes or less in duration)

(After Kryter - CHABA(139))

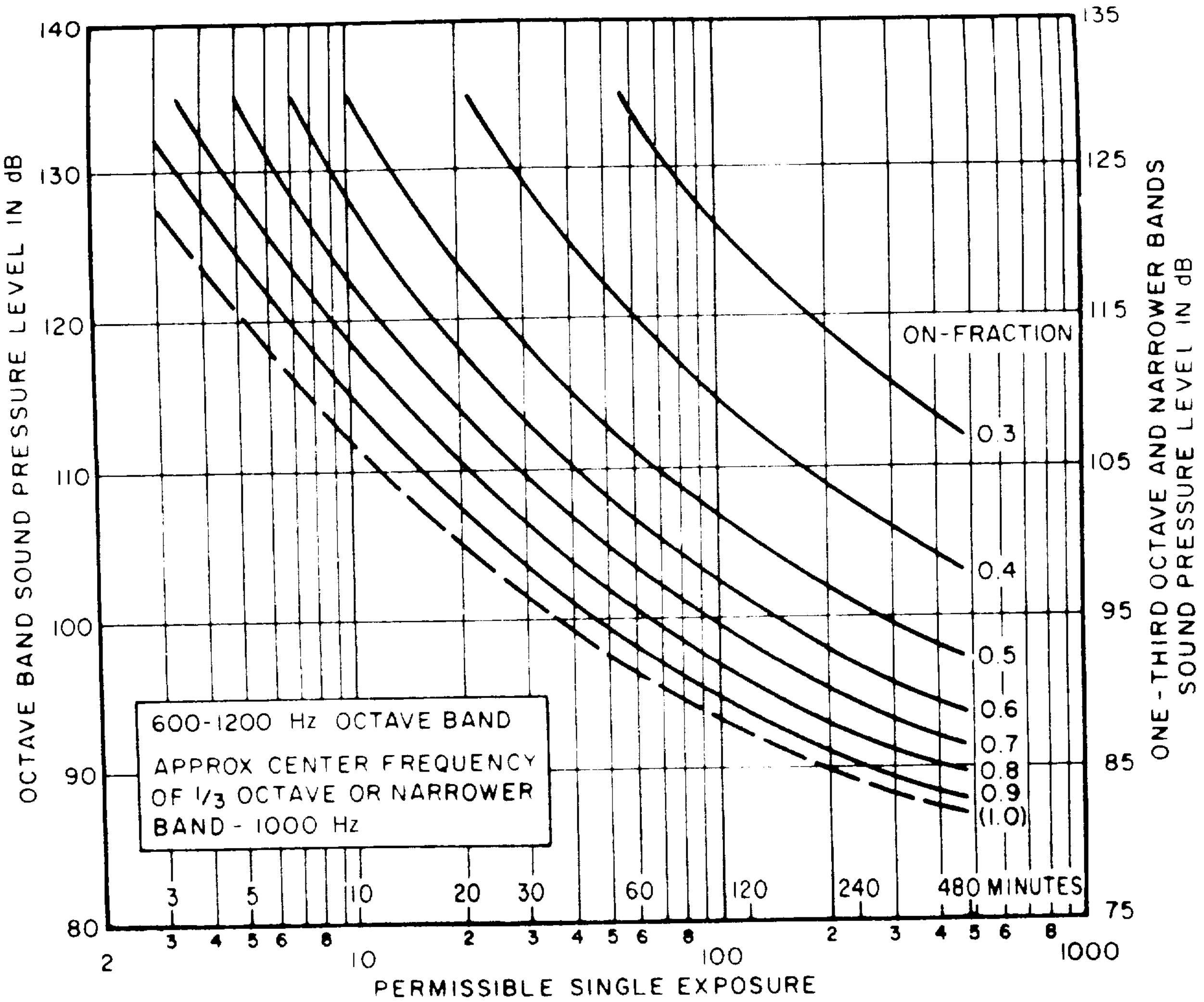


Figure 9-43

Damage Risk Contours for Short-Burst-Duration Intermittent noise

(Noise bursts 2 minutes or less in duration)

(After Kryter - CHABA[(139)])

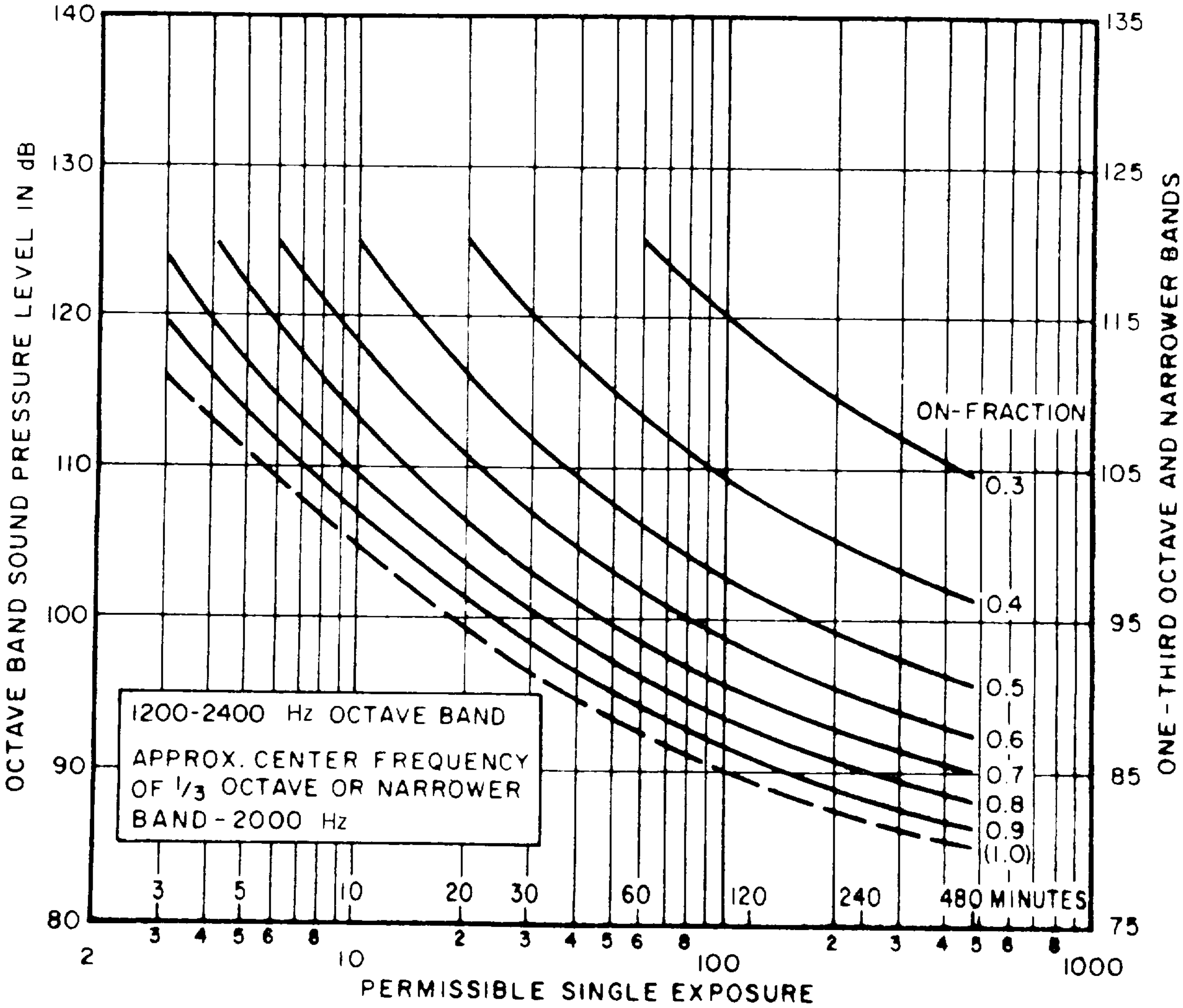


Figure 9-44

Damage Risk Contours for Short-Burst-Duration Intermittent Noise (Noise bursts 2 minutes or less in duration)

(After Kryter - CHABA[139])

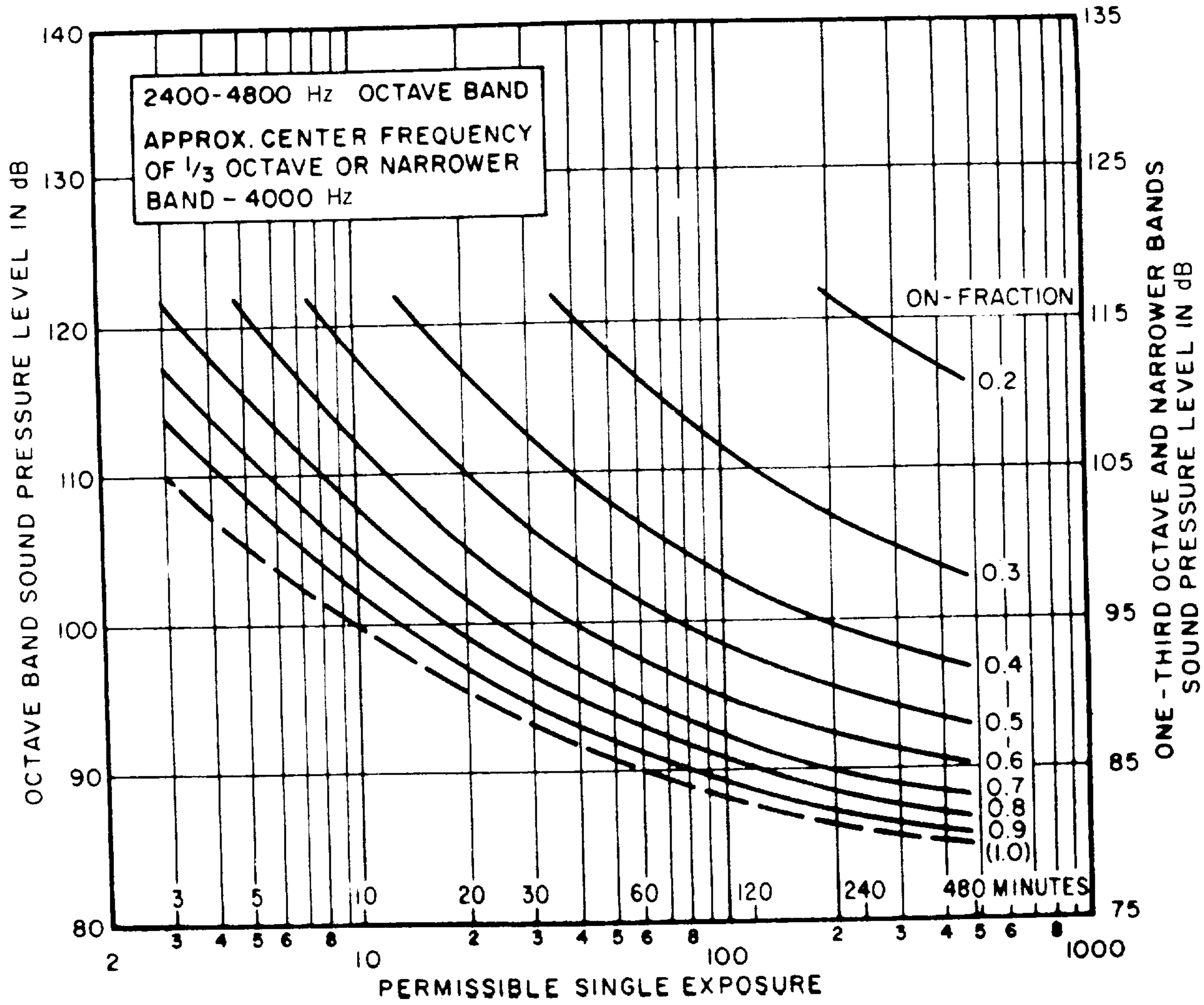


Figure 9-45

Damage Risk Contours for Short-Burst-Duration Intermittent Noise
(Noise bursts 2 minutes or less in duration)

(After Kryter - CHABA[139])

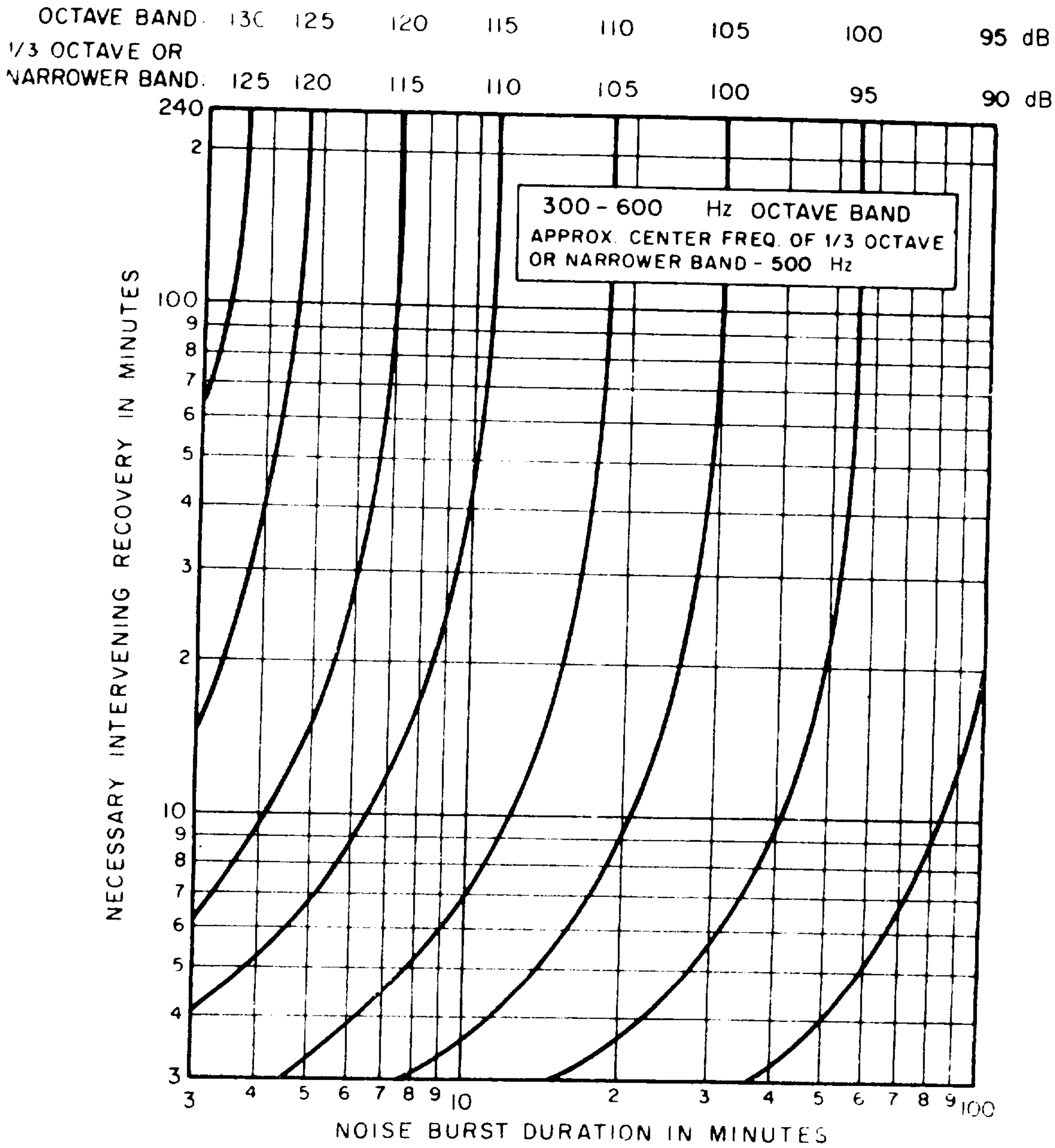


Figure 9-46

Damage Risk Contours for Long-Burst-Duration Interrupted Noise Parameter; Band SPL

(After Kryter - CHABA(139))

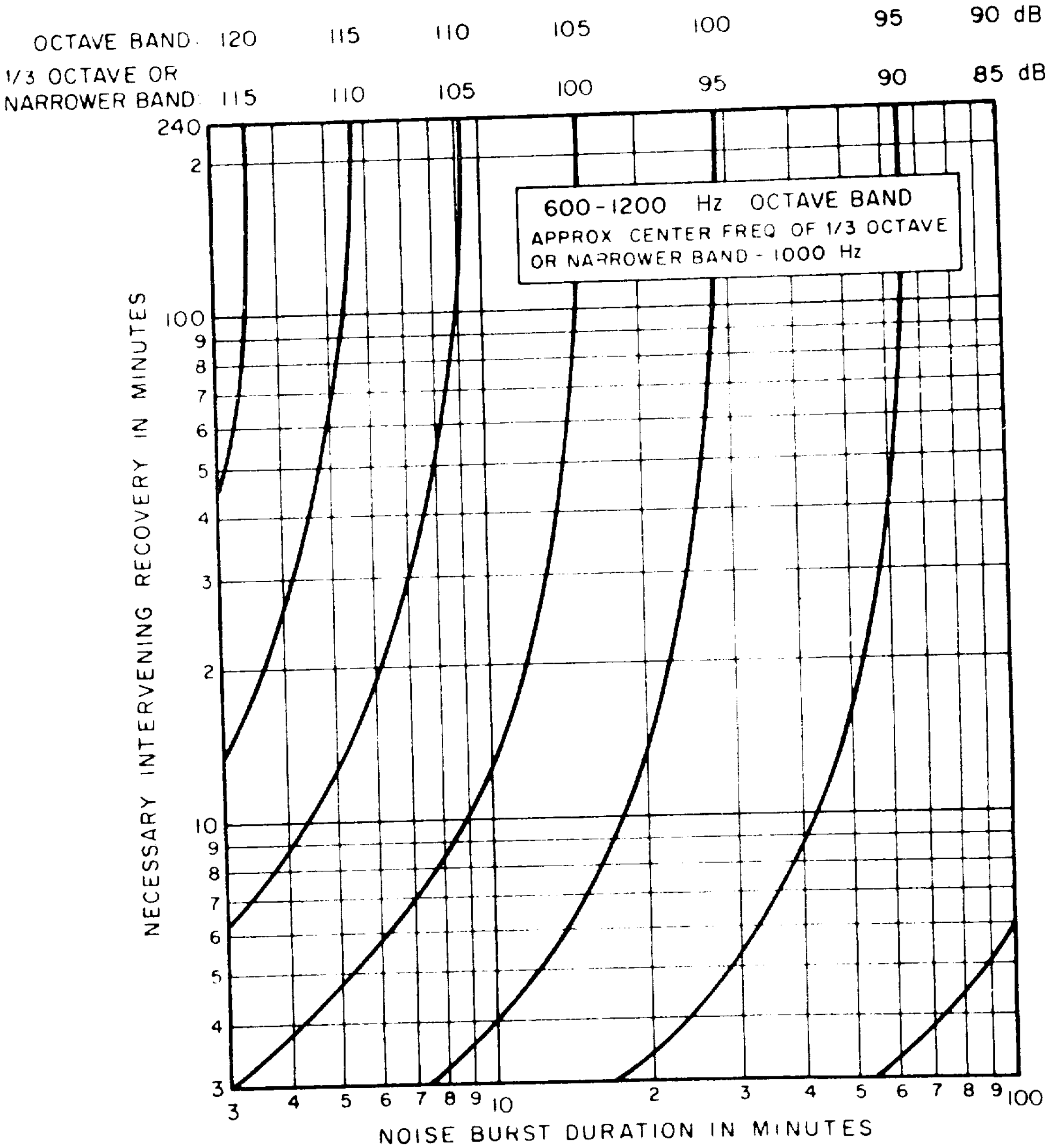


Figure 9-47

Damage Risk Contours for Long-Burst-Duration Interrupted Noise Parameter: Band SPL

(After Kryter - CHABA[139])

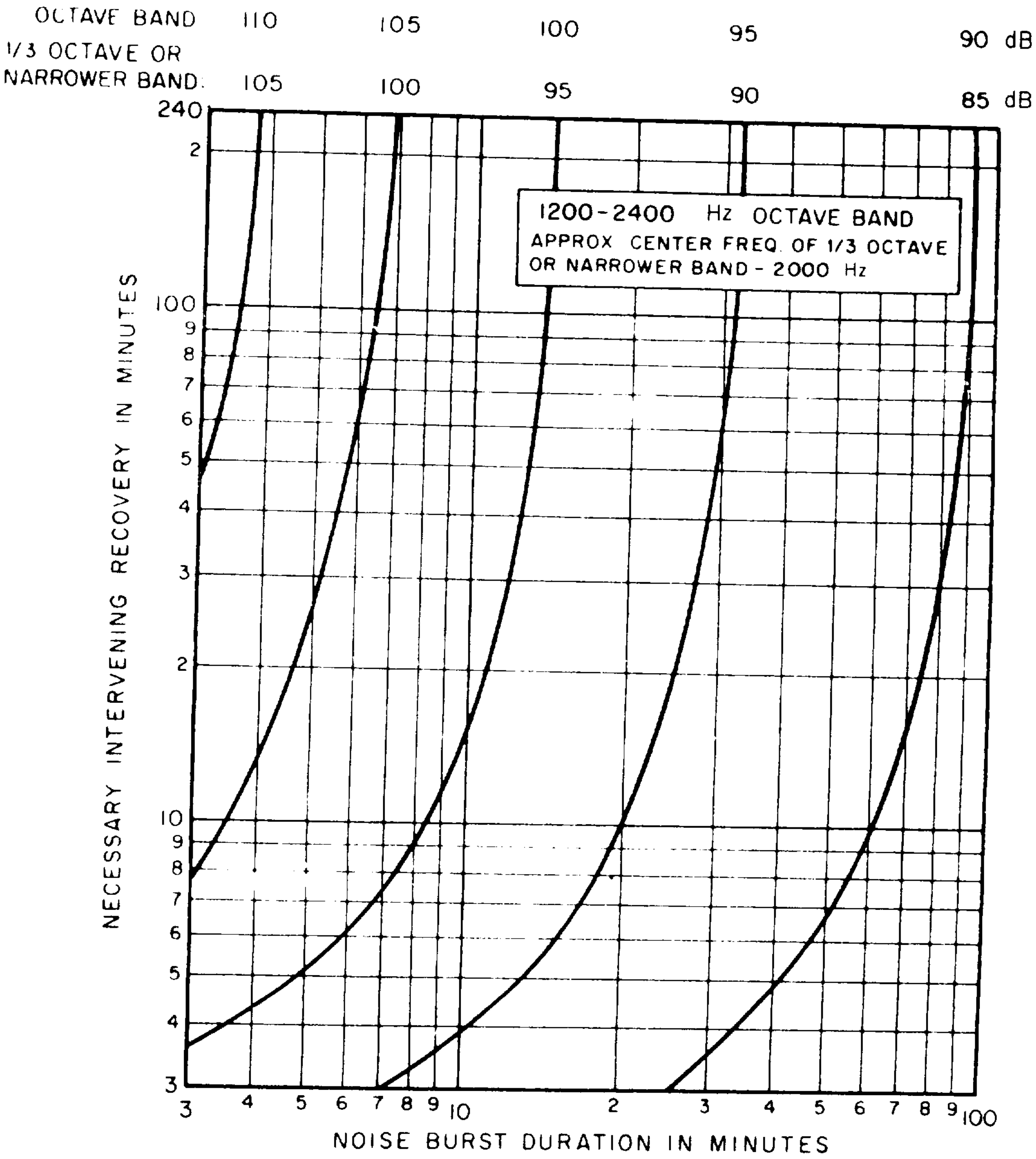


Figure 9-48

Damage Risk Contours for Long-Burst-Duration Interrupted Noise Parameter: Band SPL

(After Kryter - CHABA(139))

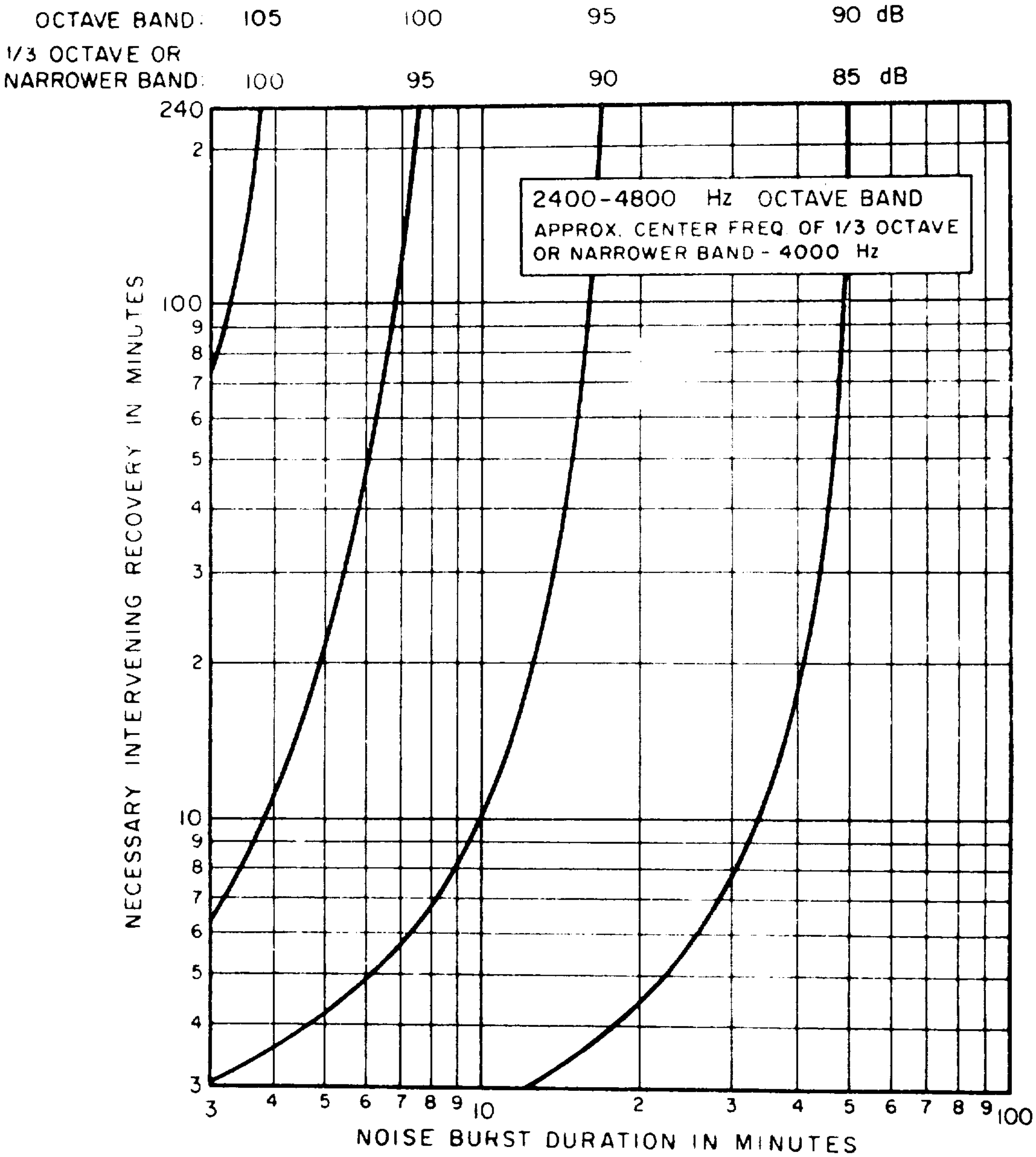


Figure 9-49

Damage Risk Contours for Long-Burst-Duration Interrupted Noise Parameter: Band SPL

(After Kryter - CHABA[139])

found on the graph, suggesting that a single 10 min exposure will probably exceed the criterion. This is verified by consulting Figure 9-39, which shows that a single 9 min exposure is all that can be tolerated in a single day.

Relations shown in Figures 9-39 to 9-49 are based either upon direct measures of temporary threshold shifts or permanent noise-induced losses in hearing resulting from exposure to sound or extrapolations from such data as are available. In general, there has been a sufficient amount of research in this problem area so that both the data points and extrapolations have been verified to a reasonable extent by one or more independent investigations. However, some of the relations are based on less evidence than others. For example:

- The maximum levels to be allowed regardless of duration (the top curves of Figures 9-39 and 9-41) are estimates that are not supported by direct experimental data.
- The data supporting the damage risk contours for pure tones are not as extensive as those for the octave or one-third octave bands of noise, and as such may be subject to change. Because of the extensiveness and similarity of results found with bands of noise by various investigators, it is felt that the damage risk contours for bands of noise are valid.
- As yet, there are very few data on the effects of sounds below 100 Hz and above about 7000 Hz. (See Figure 9-36a and b). In the opinion of the Working Group, there is at the present time insufficient evidence to warrant extrapolating the damage risk contours as a function of frequency beyond the frequencies mentioned.
- It is found that noises that are one octave in width will provide a degree of shift in threshold of audibility similar to that resulting from exposure to a one-third octave band having the same center frequency, but 5 dB less intense than the octave band of noise (112, 116). Further verification of this result is needed, however, before this difference between the effect on hearing of one-third and octave bands of noise having the same center frequency can be considered as proven.

As will be seen from a comparison of Figures 9-40 and 9-41, the ear is less tolerant of low-frequency pure tones than it is to narrow bands of noise in the same frequency region. The explanation for this difference is apparently to be found in the actions of the aural reflex (200, 201). This reflex is such that when the ear is exposed to intense bands of noise, it can provide, depending on the level, as much as 15 dB or so of effective protection for low-frequency sounds being transmitted to the inner ear. However, the reflex is not maintained by pure tones, and as a result the tolerable sound pressure level for low-frequency tones below 1000 Hz is much less than it is for bands of noise with frequencies below 1000 Hz.

Data are available on the center and cutoff frequencies of commercially available filters for noise control work (139).

Since pain is produced by overall sound pressure levels exceeding 135 dB, the unprotected ears should not be exposed to levels exceeding this level, no matter how short the exposure period. Because of nonauditory effects (possible disorientation, nausea, vomiting) exposure of personnel is usually restricted to noise levels below 150 dB, no matter how short the exposure time nor how much the noise level in the ear canal is reduced by ear protectors. In experiments with special precautions and close observation, people have been exposed with ear protection to higher levels without harm (see Figure 9-36).

If the combination of ambient noise levels and exposure times exceeds the damage risk criteria discussed, reduction of the ambient noise or personally worn ear protective devices are necessary to reduce the noise received by the ear to levels below the exposure criteria.

In reality, the damage risk contours discussed above have no sharp limits but are based on rather broad probability distributions. Therefore, they cannot be taken too literally (68). Nevertheless these contours serve as helpful guides for the advisability of noise control measures, the wearing of personal protection equipment or for reducing the exposure time. These criteria should be applied only for almost daily, repeated, routine exposures as applicable to aircraft ground crew or rocket test crews. They could be exceeded, if necessary, for short, infrequent special operations.

Routine exposure of personnel to hazardous noise levels as discussed here should always be monitored by a medical hearing-conservation program (192, 194). The intricate problem of the intrusion of aerospace noise into communities has been reviewed in detail (15, 28, 48, 82, 156, 182). (See also sonic booms above). Control of booster noise at launch complexes and test stands should make use of these principles.

Recent recommendations for control of noise in military aircraft and helmets have been published (196). They should be valid for use in NASA support aircraft. Table 9-50 covers these data. The acoustical noise level in any part of the aircraft intended for occupancy by the crew or other personnel cannot exceed the values specified in Table 9-50a, Part I (preferred) or Table 9-50a, Part II, during conditions of maximum continuous power. For takeoff, afterburner operation and other conditions normally not exceeding 5 minutes continuous duration the acoustical noise level in any part of the aircraft intended for occupancy by the crew or other personnel cannot exceed the values specified in Table 9-50b, Part I (preferred) or Table 9-50b, Part II.

In aircraft in which personnel must necessarily wear helmets at all times and communicate by electronic means (e. g., single place fighter aircraft), the acoustical noise level cannot exceed the values specified in Table 9-50c, Part I (preferred) or Table 9-50c, Part II during conditions of maximum continuous power. The acoustical noise level in any part of the aircraft intended for occupancy by the crew or other personnel cannot exceed the values specified in Table 9-50d, Part I (preferred) or Table 9-50d, Part II, during conditions of normal cruise power.

Table 9-50

Allowable Acoustical Noise Levels in Military Aircraft and Helmets (See text)

(After MIL-A-8806A$^{(196)}$)

a. Maximum Acceptable Noise Level at Maximum Continuous Power

I		
Frequency (Hz)		Max. acceptable noise level (dB)
Band	Center	
Overall		113
22.4 - 45	31.5	111
45 - 90	63	111
90 - 180	125	111
180 - 355	250	111
355 - 710	500	105
710 - 1400	1000	99
1400 - 2800	2000	93
2800 - 5600	4000	87
5600 - 11200	8000	87

II	
Frequency bands (Hz)	Max. acceptable noise level (dB)
Overall	113
37.5 - 75	111
75 - 150	111
150 - 300	111
300 - 600	105
600 - 1200	99
1200 - 2400	93
2400 - 4800	87
4800 - 9600	87

b. Maximum Acceptable Noise Level Under Short Duration Conditions

I		
Frequency (Hz)		Max. acceptable noise level (dB)
Band	Center	
Overall		120
22.4 - 45	31.5	118
45 - 90	63	118
90 - 180	125	118
180 - 355	250	118
355 - 710	500	112
710 - 1400	1000	106
1400 - 2800	2000	100
2800 - 5600	4000	94
5600 - 11200	8000	94

II	
Frequency bands (Hz)	Max. acceptable noise level (dB)
Overall	120
37.5 - 75	118
75 - 150	118
150 - 300	118
300 - 600	112
600 - 1200	106
1200 - 2400	100
2400 - 4800	94
4800 - 9600	94

c. Maximum Acceptable Noise Level with Protective Helmets or Devices

I		
Frequency (Hz)		Max. acceptable noise level (dB)
Band	Center	
Overall		113
22.4 - 45	31.5	111
45 - 90	63	111
90 - 180	125	111
180 - 355	250	111
355 - 710	500	109
710 - 1400	1000	106
1400 - 2800	2000	100
2800 - 5600	4000	94
5600 - 11200	8000	94

II	
Frequency bands (Hz)	Max. acceptable noise level (dB)
Overall	113
37.5 - 75	111
75 - 150	111
150 - 300	111
300 - 600	109
600 - 1200	106
1200 - 2400	100
2400 - 4800	94
4800 - 9600	94

d. Maximum Acceptable Noise Level at Normal Cruise Power

I		
Frequency (Hz)		Max. acceptable noise level (dB)
Band	Center	
Overall		106
22.4 - 45	31.5	104
45 - 90	63	104
90 - 180	125	104
180 - 355	250	104
355 - 710	500	96
710 - 1400	1000	90
1400 - 2800	2000	86
2800 - 5600	4000	75
5600 - 11200	8000	75

II	
Frequency bands (Hz)	Max. acceptable noise level (dB)
Overall	106
37.5 - 75	104
75 - 150	104
150 - 300	104
300 - 600	96
600 - 1200	90
1200 - 2400	86
2400 - 4800	75
4800. - 9600	75

A Soviet analysis of the acoustical environment for space cabins is available (211).

Personal Protective Equipment

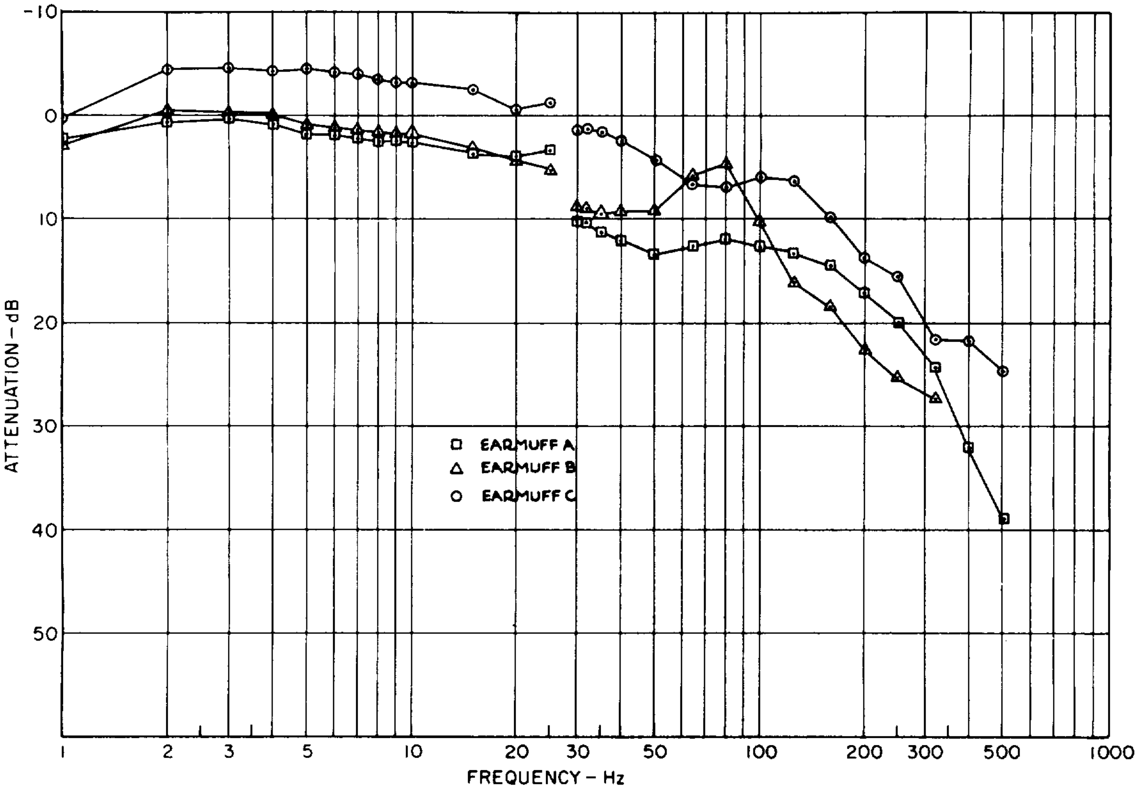
Personal protective equipment against degradation of performance by noise appears to be an optimum approach in many aspects of controlling the sound environment. In general there is no difficulty in providing adequate protection by comfortable personal equipment (earplugs, earmuffs, or properly designed and fitted helmets). Their effectiveness has been shown to be almost ideal and can hardly be improved (21, 22, 29, 56, 66, 71, 82, 133, 146, 160, 174, 213). Electroacoustic ear protectors are under design for impulse noise (197). Data are available on the effect of earmuffs in the low and infrasonic frequencies (145). (Figure 9-51a). The findings of this investigation demonstrate that "good" present-day earmuff protectors provide about 10 dB of sound attenuation at frequencies between 20 and 100 Hz and very little attenuation below 20 Hz. For optimum ear protection in intense sound fields with high concentrations of acoustic energy in the low audio frequency and infrasonic regions, good insert earplugs are recommended for short duration exposures. For long-time exposures, the use of good earmuffs in combination with insert earplugs is recommended. These data confirm, quantitatively, subjective observations (Figures 9-36a and b) of the performance of muff-type ear protectors in intense infrasonic and low audio-frequency noise environments.

The use of ear protection improves the intelligibility of direct voice communication in high noise environments (90). For space cabins, helmets to be worn during high-noise phases of the mission (boost phases and reentry) and the communication system have to be designed so that these criteria can be met. The reduction of ambient noise achieved by various representative earmuffs and helmets is illustrated in Figure 9-51b. Figure 9-29 covers the effect of earplugs on improving the intelligibility of speech in noisy environments. Figure 9-52 presents the nominal noise reduction values for a NASA helmet and earmuffs combination (194). Oxygen masks or the face plates of pressure helmets can give approximately 15 dB or more attenuation in the speech frequency range. (See also Table 9-50c)

Auditory signals for malfunction must be audible in the presence of external noise on liftoff. In general, auditory warning signals on spacecraft must be easily detectable, must hold the operator's attention, and must be quickly and accurately identifiable (198). The signal should therefore be easily distinguishable from background noises. Warbling or wailing tones may be used in order to be distinguishable from ambient noises. The sound should be at least 20 decibels above threshold and frequencies below 500 cycles per second should not be used. It is also recommended that signals which cause operator discomfort; e. g., continuous high pitched tones of frequencies above 200 cycles per second, not be used. The signal should be as brief as possible but still be identifiable.

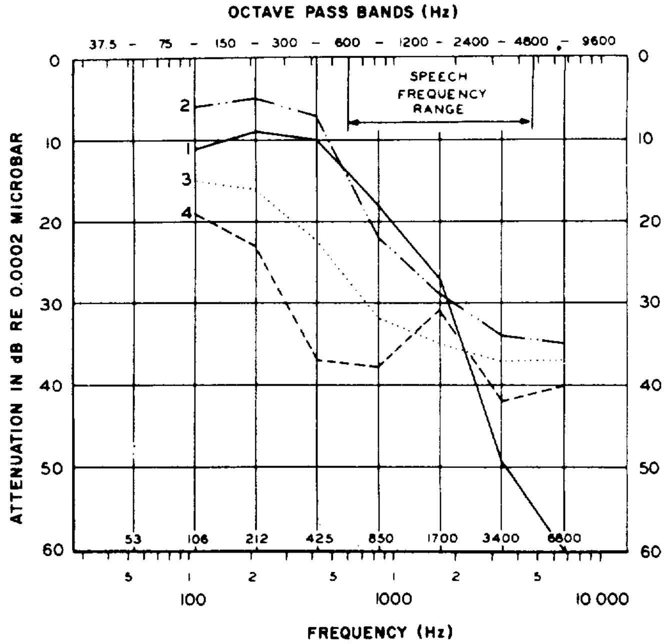
Figure 9-51

Attenuation of Noise by Earmuffs and Helmets



a. Physical Measurement of Earmuff Attenuation of Low Frequency Sound

(After Nixon et al(145))



b. Reduction of Ambient Noise of Different Frequencies Provided by Various Types of Helmets and Earmuffs

1. Full pressure helmet with earmuffs inside providing a poor seal around the ear (thin sponge rubber seal).
2. Protective flying helmet with earmuffs inside (thin sponge rubber cushion; poor seal).
3. Protective flying helmet with effective earmuffs (liquid filled cushion; good seal)(209).
4. Effective earmuffs (liquid filled cushion; good seal) with headset inside for use by ground crews. This earmuff has a larger air volume under the muff than the earmuff used in the protective helmet above(11) and therefore it provides more attenuation.

(After von Gierke and Hiatt(71))

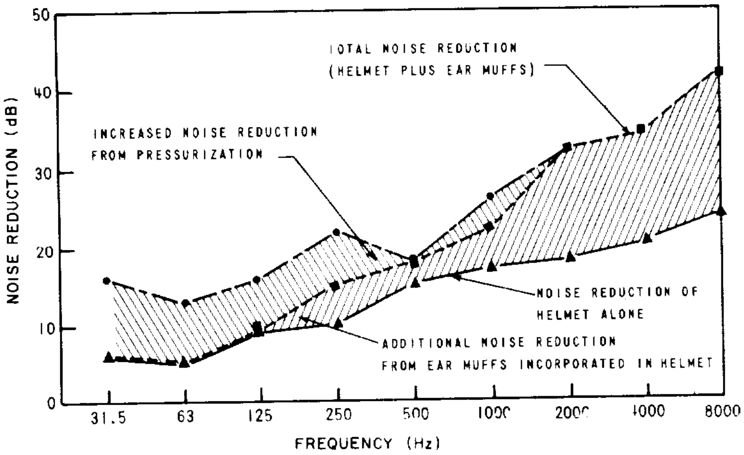


Figure 9-52

Nominal Noise Reduction Values for the Addition of Ear Muffs to NASA Helmets

(After AFSCM(194))

In the Apollo spacecraft Caution and Warning Subsystem, in addition to indicator lights for malfunctions, an audible signal is provided to alert the crew to existing out-of-tolerance conditions. The intensity level of the audio tone is 78 dB as measured at the instrument panel. It is a two-tone alternating signal, consisting of tones of 2000 and 750 Hz, with 2-1/2 switches per second. The Caution and Warning audio tone on-board the LEM is a single tone signal of 3200 Hz also at 78 dB measured at the instrument panel.

As covered in the section on speech intelligibility, filters in communications systems can be used for enhancing the audibility of signals in the presence of noise. This is accomplished by the passing of certain wanted frequencies and the exclusion of unwanted ones. Two types of signal masking can be reduced by filtering:

1. Masking produced by components within a critical bandwidth centered at the signal frequency (direct masking) and,
2. Masking effects of tonal noises on signals lying outside the critical band (remote masking).

For reduction of direct masking, very narrow band-pass filters that reject noise within the critical band should be used to reduce masking of wideband on a tone that lies on a frequency which is within the noise spectrum. This band-pass filter must be narrower than the critical band or else it will only reject noise that has no masking effect.

The role of noise shields and noise-canceling microphones has been covered in the section on speech intelligibility. Figure 9-30 presents quantitative data on these effects. Recommendations for microphones and earphones in Apollo are indicated on page 9-39.

Specification of sound levels during extravehicular operations on the lunar surface indicate that acoustical levels generated by the PLSS shall not exceed the noise sound pressure level of 80 dB overall and 55 dB in the 300-4800 Hz range within the PGA helmet (198).

ANALYSIS OF SOUND AND NOISE FACTORS IN ASTRONAUT PERFORMANCE

The design and operation of the following systems and equipment are involved in the auditory performances and tolerances of the astronauts;

- Control and display system of command modules and secondary vehicles
- Intercommunications equipment
- Cabins
- Helmet and earplugs

The auditory performances and tolerances of the astronauts are considered to be a function of several factors. The basic auditory capabilities and tolerances of the astronaut population (or equivalent population) must be measured under standard conditions. To this is added or subtracted, as appropriate, the effects of the environment (e. g., the ambient noise levels, pressure levels, etc.); the equipment (e. g., signal-to-noise ratio of the intercommunication equipment, attenuation of noise by helmets, etc.); the operations (e. g., whether face-to-face verbal communications or intercommunication equipment are used, etc.); and personnel variables (e. g., attention, age fatigue, etc.).

There are some areas where it may be possible to construct mathematical models which will permit the handling of the complex interactions that are involved in many of the areas. Such models will have the advantage of indicating how individual variables can be manipulated in order to provide more than one way of arriving at an acceptable design endpoint in noise control.

As a first approach to this problem, the ambient noise levels expected within the spacecraft during all modes of an operation should be estimated as precisely as they can be at this time. This should include the spectral characteristics of the noise and the durations. Also, the noise attenuation characteristics of the environment and equipment planned for the specific system should be determined; e. g., effects of pressure levels in the cabins and pressure suit, use of earphones and helmet, etc.

A determination should then be made of transmission characteristics of the voice communication equipment. This involves determination of the signal-to-noise ratio, type of speech processing, frequency characteristics, and microphone and earphone noise pickup characteristics, etc., specified for the voice communication equipment, including the ground-to-spacecraft between command and secondary modes and between both primary and secondary modules and lunar or planetary surfaces.

Based on the task analyses available, those tasks which involve auditory performances should be identified. This includes: (1) the characteristics of the tasks (e. g., language content, redundancy, frequency of communication, etc.), (2) relationship to the other tasks, and (3) the environmental conditions which can be expected to exist at the same time.

Once the performances that are expected of the astronauts and the conditions under which they must be performed have been identified, then these should be compared with the performance and tolerance factors contained in this compendium. Comparison of the compendium with the performances, environments, etc., should indicate whether:

- The sound level of the auditory signal devices is sufficiently above the ambient noise levels to permit reception of the signal.
- The auditory devices are sufficiently distinctive to permit discrimination between them under all ambient noise conditions.
- The ambient noise level is sufficiently low in either the shirtsleeve or pressure suit environments, to permit face-to-face verbal communications when required with an acceptable level of intelligibility, with half effort.
- The signal-to-noise ratio and bandwidth for the intercommunication equipment is sufficiently high to permit an acceptable level of intelligibility.
- The ambient noise level does not exceed intensity levels and durations which cause undue discomfort or could be expected to cause temporary or permanent damage.

Based on these comparisons if there are any areas disclosed in which performance and or tolerance limits are exceeded or marginal, analyses should be performed to determine where corrections can be made. These include:

- Reduction of the ambient noise level at its source.
- Reduction of the ambient noise level in the cabins through the use of sound absorbing materials.
- Reduction of the ambient noise level at the ear through the use or modifications of helmet, earphones, and/or earplugs.
- Modification of the auditory signal devices to increase the signal-to-noise ratio and/or distinctiveness.
- Modification of the intercommunication equipment to increase the intelligibility.
- Modification in the mode of operation to be less dependent on auditory signal devices and/or verbal communications, with the appropriate programming of face-to-face and interphone modes.

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