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Technical Memorandum 10-73

**NOISE AND BLAST**

David C. Hodge  
Georges R. Garinther

June 1973

**HUMAN ENGINEERING LABORATORY**



**ABERDEEN PROVING GROUND, MARYLAND**

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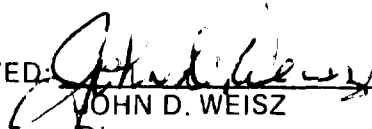
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## FOREWORD

Chapter 15 is reprinted from J. F. Parker, Jr. and V. R. West (Eds.) Bioastronautics Data Book (2nd Ed.), National Aeronautics and Space Administration, Washington, D. C., 1973, pages 693-750.

Although this report presents much background material and describes the latest research results of many facets of acoustics, current requirements for the noise levels of Army materiel are found in MIL-STD-1474(MI), Military Standard Noise Limits for Army Materiel, dated 1 March 1973.

## ABSTRACT

The effects of noise and blast upon man are complex and varied. Although this report is directed primarily toward the noise produced during space activities the effects upon man will be similar regardless of the specific noise source.

Data are presented dealing with physical acoustics, the characteristics of sound and appropriate noise measurement techniques. Hearing loss resulting from both steady-state and impulse noise is discussed along with the factors influencing its acquisition and recovery and the resultant effects upon performance. Subjective and behavioral response to noise is discussed in terms of masking of auditory signals and speech, annoyance and general observation. Current research in the area of nonauditory effects is reviewed varying from cardiovascular alterations to the risk of death.

Current design criteria are presented for both steady-state and impulse noise for both workspaces and communities.

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## CHAPTER 15

### NOISE AND BLAST

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Noise and blast problems may occur in all phases of aerospace activities. Tremendous quantities of acoustical energy are developed by rocket engines on the launch pad and during lift-off, and this may affect ground personnel as well as the crew on board the space vehicle. As payloads become larger and boosters increase in size and power, significant increases in noise and blast problems may be expected. Noise from equipment used in assembling and static testing of boosters and payloads may adversely affect ground-support personnel. In mission-control centers, noise from computers and monitoring devices may interfere with voice communications. Current evidence suggests that noise and blast problems in future space operations may be more severe at ground-service crew locations and in nearby communities than in the space vehicles themselves. However, control of noise levels inside spacecraft will still require consideration in assessing the likelihood of mission success.

The most significant effects of noise and blast on man are damage to hearing, masking of speech and warning signals, and annoyance. In addition, noise interferes with some of man's sensory and perceptual capabilities and thereby may degrade critical task performance. Noise also produces temporary or permanent alterations in body chemistry.

This chapter describes the noise and blast environment. It provides a definition of units and techniques of noise measurement and gives representative booster-launch and spacecraft noise data. It reviews the effects of noise on hearing sensitivity and performance and discusses briefly community response to noise exposure. Physiological, or nonauditory, effects of noise exposure are also

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Reviewed by Henning E. von Gierke



treated, as are design criteria and methods for minimizing the effects of noise on hearing sensitivity and on communications. The references cited in this chapter relate primarily to research conducted during the past 10 years in the United States and several foreign countries.

## Description of the Noise and Blast Environment

### Definitions and Units

Airborne sound refers to a rapid variation in ambient atmospheric pressure. By definition, noise is unwanted sound. *Steady-state* noise is a periodic or random variation in atmospheric pressure which has a duration in excess of 1000 milliseconds. *Impulse* noise is a nonperiodic variation in atmospheric pressure which has a duration of less than 1000 msec, and a peak to root-mean-square (RMS) ratio greater than 10 decibels (dB). Blast is an anomalous term, but is most frequently used to describe very large amplitude and/or long duration pressure waves accompanying the discharge of large-caliber weapons, the ignition of rocket motors, or the detonation of conventional and nuclear explosives. Taken together, sound, noise, and blast all refer to airborne acoustical phenomena whose energy may be described both in terms of their physical characteristics (amplitude, frequency content, and/or duration) and their effects on man's physiology and behavior.

*Amplitude* The amplitude of sound at any given point is expressed as sound-pressure level (SPL). Its physical unit is the decibel which is given as:

$$\text{SPL} = 20 \log (p/p_o) \text{ in dB}$$

where  $p$  = the sound pressure being measured; and  $p_o$  = a reference pressure, usually 20 micronewtons per square meter ( $\mu\text{N}/\text{m}^2$ ). The reference pressure of  $20 \mu\text{N}/\text{m}^2$  is approximately equal to the lowest pressure which a young person with normal hearing can barely detect at a frequency of 1000 Hertz (Hz). Other measures of sound pressure may be encountered in the literature, such as dynes per square centimeter ( $\text{dyn}/\text{cm}^2$ ), microbar ( $\mu\text{bar}$ ) and pounds per square inch (psi). Table 15-1 shows the relationship between four such measures.

Common examples of representative SPL include:

|                                  |       |
|----------------------------------|-------|
| A business office                | 50 dB |
| Speech at 3 feet                 | 65    |
| Subway at 20 feet                | 95    |
| Jet aircraft at 35 feet          | 130   |
| Atlas launch at 150 feet         | 150   |
| On gantry during Saturn V launch | 172.  |

Table 15-1  
Relationship Between Decibels, Newtons/Meter<sup>2</sup>,  
Microbar\*, and Pounds/Inch<sup>2</sup>

| dB  | N/m <sup>2</sup> | μbar    | PSI                      |
|-----|------------------|---------|--------------------------|
| 0   | 0.00002          | 0.0002  | 2.94 X 10 <sup>-9</sup>  |
| 14  | 0.0001           | 0.001   | 14.70 X 10 <sup>-9</sup> |
| 34  | 0.001            | 0.01    | 147.0 X 10 <sup>-9</sup> |
| 54  | 0.01             | 0.1     | 1.47 X 10 <sup>-6</sup>  |
| 74  | 0.1              | 1       | 14.70 X 10 <sup>-6</sup> |
| 94  | 1                | 10      | 147.0 X 10 <sup>-6</sup> |
| 114 | 10               | 100     | 1.47 X 10 <sup>-3</sup>  |
| 134 | 100              | 1000    | 14.70 X 10 <sup>-3</sup> |
| 154 | 1000             | 10 000  | 147.0 X 10 <sup>-3</sup> |
| 174 | 10 000           | 100 000 | 1.47                     |

\*Also note that 1 μbar = 1 dyn/cm<sup>2</sup>.

*Velocity.* The speed of sound is dependent only upon the absolute temperature of the air, assuming that air behaves as an ideal gas. The equation for the speed of sound (C) in meters per second is:

$$C = 20.05 \sqrt{T} \text{ m/sec}$$

where T is the absolute temperature in degrees Kelvin (273.2° plus the temperature in degrees Centigrade). Thus the speed of sound at 21.1° C is about 344 m/sec.

In English units:

$$C = 49.03 \sqrt{R} \text{ ft/sec}$$

where R is the temperature in degrees Rankine (459.7° plus the temperature in degrees Fahrenheit). Again, at 70°F, the speed of sound is about 1128 ft/sec.

*Wavelength.* The wavelength (λ) of a sound is the distance the wave travels during one period or cycle. It is related to the speed of sound and to frequency by the equation:

$$\lambda = \frac{c}{f}$$

where  $c$  = speed of sound (m/sec or ft/sec), and  $f$  = frequency (Hz). For example, during one period a 100 Hz wave would move 3.44 meters or 11.3 feet at 70°F (21.1°C). It is helpful to keep in mind that as frequency increases, wavelength becomes shorter.

**Frequency.** The unit of frequency is Hertz (Hz) or cycles per second (cps). Nominally, the range of aurally detectable sounds is 20 to 20,000 Hz. Pressure oscillations at frequencies above this range are called ultrasonic. These frequencies cannot normally be heard by man but they do produce some biological effects and will be discussed in a later section. The effects of infrasonic frequencies (<20 Hz) will also be discussed briefly. The terms supersonic and subsonic, which are related to the speed of sound, should not be confused with those terms which describe frequency range.

When describing sound, noise or blast, it is not sufficient to measure only the overall SPL. The noise must also be analyzed to determine how the sound energy is distributed over the frequency range. A noise is usually analyzed by passing it through a constant-percentage bandwidth filter, such as an octave-band analyzer, in which each passband has upper and lower limiting frequencies having a ratio of 2:1. An octave-band analysis is usually sufficient to determine the effect of steady-state noise upon humans and the surrounding community. A 1/3-octave (or narrower) analysis is required when it is desired to localize which component in a system is the major contributor to a noise problem, or if the noise contains a pronounced narrow-band frequency component.

The preferred series of octave bands for acoustical measurements are identified as multiples and submultiples of 1000 Hz which describe the center frequency of each band. Another series of octave bands which has been widely used in the past are the commercial octave bands. These are normally described by their band-limiting frequencies.

Another type of frequency analysis which is gaining importance is the "weighting network" which is included in all sound-level meters which meet the requirements of the current American National Standards Institute's (ANSI) specification for sound level meters (ANSI, 1971). The weighting networks consist of three alternate frequency response characteristics, designated A-, B-, and C-weighting. Whenever one of these networks is used, the reading obtained must be identified properly. For instance, if an A-weighted sound pressure level of 90 is obtained, it would be reported as 90 dBA. The A-weighting network is particularly valuable if a quick estimate of the interference of noise upon speech is required (Klumpp & Webster, 1963). Also there has been a recent movement toward using the A-weighting network for evaluating the hearing hazard of steady-state noise when it is not possible or practical to perform a complete octave-band analysis (Botsford, 1967).

#### *Definitions Peculiar to Impulse Noise and Blast.*

Peak Pressure is the highest pressure achieved, expressed in dB re 20  $\mu\text{N}/\text{m}^2$ , or in psi.

Rise Time is the time taken for the single pressure fluctuation that forms the initial or principal positive peak to increase from ambient pressure to the peak pressure level.

Pressure Wave Duration (A-Duration) is the time required for the pressure to rise to its initial or principal positive peak and return momentarily to ambient pressure.

Pressure Envelope Duration (B-Duration) is the total time that the envelope of pressure fluctuations (positive and negative) is within 20 dB of the peak pressure level. Included in this time would be the duration of that part of any reflection pattern that is within 20 dB of the peak pressure level.

*Psychological Terms.* The measures of loudness are the phon and the sone. Sones are obtained by a conversion of eight octave bands into sones from an appropriate table. The phon is merely a transformation of the sone into a logarithmic scale. Sounds that are perceived as equally loud to the human ear will have the same sone or phon value. The mel is used as a subjective measure of the pitch differences in frequency between sounds.

### **Propagation of Sound**

In an ideal, homogeneous, loss-free atmosphere SPL decreases, through spherical divergence, inversely with distance in the far field. That is, there is a 6 dB decrease in SPL for each doubling of distance from the source. In addition, when sound travels through still, homogeneous air, a significant amount of energy is extracted through "molecular absorption" which is related to the relaxation behavior of the oxygen molecules. This excess attenuation depends not only on frequency, but also on temperature and humidity and is in addition to losses resulting from spherical divergence. Figure 15-1 shows engineering estimates of excess attenuation as a function of distance and frequency for air temperatures ranging from 0° to 100°F and over a relative humidity range from 10 to 90 percent. Data are given for the preferred octave bands ranging from 500 to 8000 Hz. While there is some absorption in the lower bands, it can usually be neglected. A more complete discussion of atmospheric absorption is provided by the Society of Automotive Engineers (SAE) (1964).

In certain cases "classical absorption" should also be considered. Classical absorption is proportional to the frequency squared, is independent of humidity, and its effects typically are much less than those of molecular absorption (Nyborg & Mintzer, 1955).

In addition to the preceding, the refraction of sound waves produced by meteorological conditions between the earth's surface and altitudes of 3 to 5 kilometers must be considered. This phenomenon may cause sound waves produced at or near the surface of the earth to be focused near residential areas adjacent to rocket launch sites (Perkins et al., 1960). This refraction is due to changes in velocity of sound with altitude, and it is caused by variations in temperature, humidity and wind with altitude. The SPL for various refraction

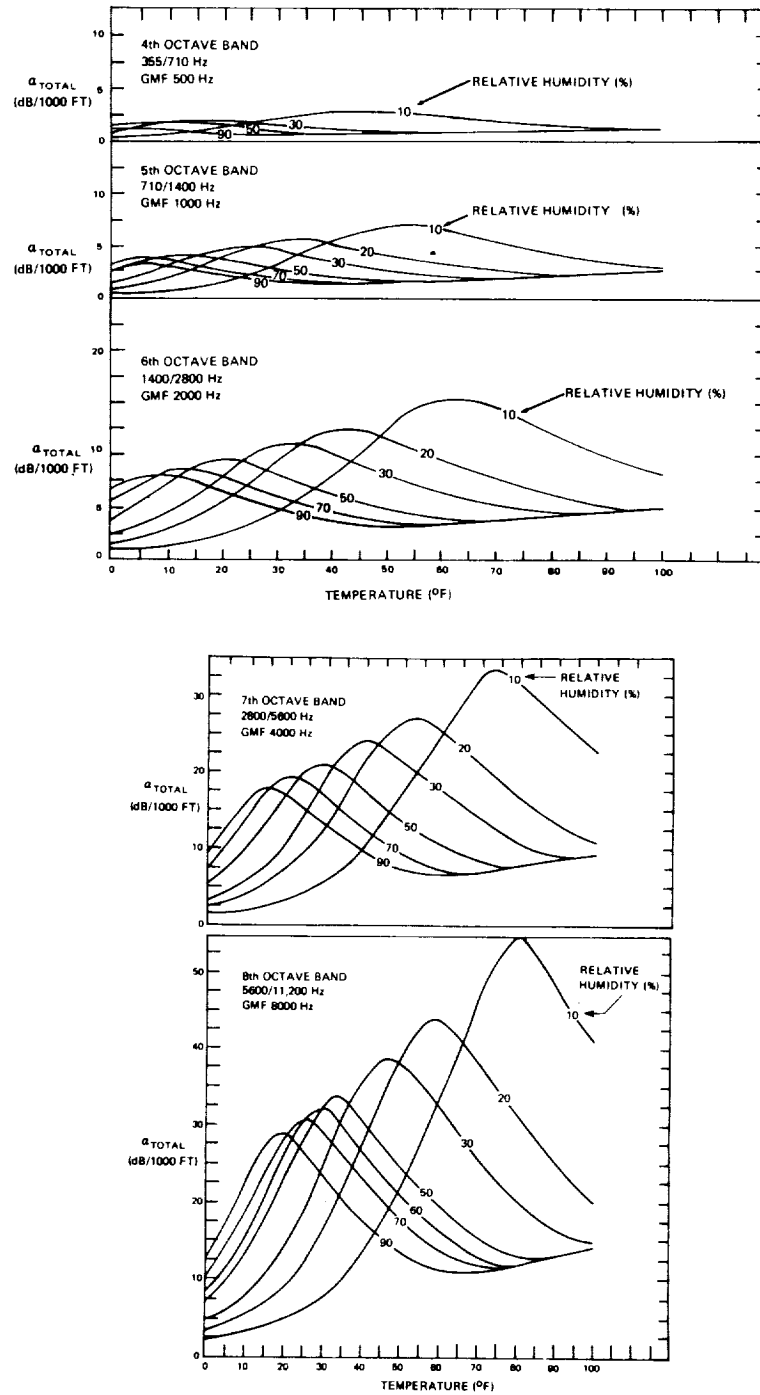


Figure 15-1. Atmospheric absorption coefficients for octave bands of noise for different temperatures. (Society of Automotive Engineers, 1964)

conditions and their focal points may be calculated by a modified ray acoustic method if the directivity characteristics of the source are known. Experience has shown, though, that quite often the effects of refraction and focusing do not occur and the SPL approaches that predicted for a homogeneous medium. Although those conditions causing focusing do sometimes occur in the Cape Kennedy area, they are not prevalent (Chenoweth & Smith, 1961).

#### Noise Measurement.

The basic measuring system for evaluating the physical characteristics of noise to relate them to their effect on man consists of the following elements:

1. transducer (microphone)
2. electronic amplifier and calibrated attenuator
3. data storage
4. octave-band analyzer
5. read-out.

The choice of instrumentation for a particular situation must be based upon a knowledge of the limitations and capabilities of the various types of instrumentation available. Normally, the weakest item of a measuring system is the transducer (microphone). Most of the discussion will, therefore, center around the selection of transducers and the techniques to be used in measuring steady-state and impulse noise. The associated equipment will naturally require characteristics which are as good as, or better than, those of the microphone selected.

*Steady-State Noise.* Microphones are available in a variety of sensitivities. When very low noise levels are to be measured, the minimum SPL to which a microphone can respond should be the determining factor in selection. It must also be ascertained that the self-noise of the microphone (and the entire measuring system for that matter) is at least 10 dB below the noise that is to be measured *in each octave band of interest*. On the other hand, for measuring high-level noises such as those produced by rocket engines, the choice of microphone to be used will be limited by the maximum SPL to which the microphone can respond without excessive distortion or failure. After the preceding two considerations have narrowed the selection, the microphone that should be selected is the one having the smoothest frequency response over the range of interest.

The frequency response of most microphones varies with the direction of arrival of the sound wave. At low frequencies (below 1 kHz), where the size of the microphone is small in relation to the wavelength of sound, microphones are omnidirectional. However, at higher frequencies the direction in which the microphone is pointed, or its incidence angle\*, must be carefully considered.

---

\*The incidence angle for most microphones is that angle subtended between its longitudinal axis and a line drawn between the noise source and the microphone.

The manufacturer's specifications should be consulted to obtain the incidence angle which provides the smoothest possible frequency response.

If a moving noise source is to be measured, a microphone which has its best response at  $0^\circ$  (normal) incidence should not be used since the measured spectrum will change with noise-source location. Therefore, in this case, it would be desirable to select a microphone with good response at  $90^\circ$  (grazing) incidence and to position it so the moving noise source is always at  $90^\circ$  incidence to the microphone.

**Impulse Noise and Blast.** The measurement of impulse noise presents several problems which must be discussed separately. The principal limitations in the measurement of impulse noise lie in the ability of the transducer and its associated equipment to respond to the pressure pulse accurately (Garinther & Moreland, 1965; Coles & Rice, 1966). The minimum qualities of the transducers and associated equipment for such measurements are:

1. A good phase response.
2. A uniform amplitude response characteristic over a wide frequency range. [A bandwidth of from 100 Hz to 70 kHz is adequate for measuring most short duration impulses such as from small arms, but longer duration impulses such as from large caliber weapons and sonic booms require an extension of the low frequency response, and may permit relaxation of the upper limit (Crocker, 1966).]
3. Less than 1.5 dB ringing and overshoot at the pressure being measured (ringing should be completely damped after 100  $\mu$ sec).
4. Rise time capability of 10  $\mu$ sec or less *at the pressure being measured*.
5. Sufficient robustness to withstand damage from the pressure pulse being measured.
6. Mounting of all apparatus to eliminate microphonics.
7. Sufficient sensitivity to allow a signal-to-noise ratio of 25 dB or greater.
8. Minimum drift caused by temperature instability.

The *angle of microphone incidence* is even more important for measuring impulse noise than for measuring steady-state noise. Garinther and Moreland (1965) have shown that at  $0^\circ$  (normal) incidence, the measured peak pressure level of various microphones may differ by as much as 10 dB. Since the peak readings obtained from various microphones should theoretically be, and were in fact found to be, in good agreement at  $90^\circ$  incidence, the transducer should be oriented for impulse-noise measurements at an angle of  $90^\circ$  (grazing incidence) between the longitudinal axis of the transducer and the direction of travel of the pressure pulse or shock wave.

With the transducer positioned at grazing incidence, rise-time characteristics will be affected by the transit time of the wave across the sensing element. Therefore, it is necessary that the transducer selected have a sensitive diameter of about 4mm or less.

Two precautions must be stated regarding the measurement and analysis of short-duration impulse noise. First, great care must be taken in interpreting the results of a frequency analysis. [Pease (1967) has published a computer program for spectrum analysis of impulse noises.] Second, in tape recording impulse noise it has been found necessary to use FM recording equipment. "Direct" (AM) tape recording produces phase shift of frequency vs. time which distorts the pressure-time history of an impulse noise.

### Prediction of Launch Noise

The primary sources which must be considered in assessing mission-associated noises are: (1) static and preflight tests, (2) launch, and (3) flight operations. Consideration must be given to how each of these phases of propulsion system noise affects the crew, ground-support personnel, and the surrounding community.

In addition to the propulsion system, noise generated within the command module must be carefully assessed with regard to its long-term effects upon the crew. In space, the only sources which need to be considered are those generating noise within the capsule and any structure-borne noise.

The potential noise environment should be defined as early as possible in the development of a system. Techniques are available for predicting from a knowledge of certain parameters the sound spectrum of a propulsion system. These have been shown to be accurate to within a few decibels. A brief discussion of these follows, but the reader should consult Wilhold et al. (1970) to obtain an understanding of the computations.

The area surrounding the rocket must be divided into three regions to be properly analysed. In the acoustic *near field* (within  $1\lambda$ ) no accurate predictive technique exists. The second region is the *mid-field* ( $3-5\lambda$ ). Here it is possible to calculate a dimensionless spectrum function and source position which is dependent upon frequency, using techniques outlined in Dyer (1958). From these, and the known parameters of the propulsion system, the acoustic environment may be determined. The *far field* of the noise produced by the launch of a rocket is the area with which we are most concerned in dealing with the effects of noise upon man. The predictive method for this region is quite involved and is described in detail by Wilhold et al. (1963). Excess attenuation and meteorological effects described in an earlier section must, if appropriate, be included in computation. This technique has proven to be very accurate in predicting the band pressure levels of several rocket systems.

The acoustic environment of advanced Saturn V vehicles has been calculated for strap-on configurations having 13.1 million and 32 million pounds of thrust (Wilhold et al., 1970). These are shown in figures 15-2 through 15-5.



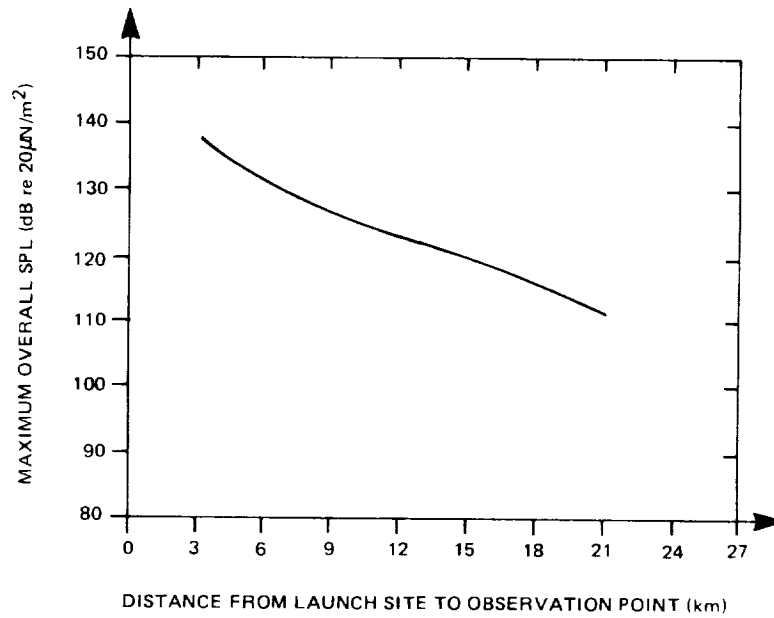


Figure 15-2. Maximum anticipated overall SPL for Saturn V MLV configuration of 32.0 million lb of thrust, as a function of distance from launch pad. (Wilhold et al., 1970)

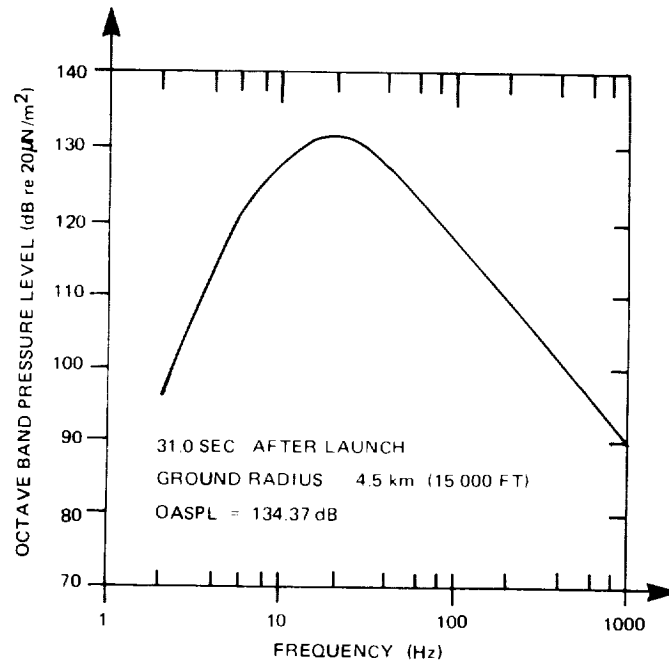


Figure 15-3. Predicted octave band pressure level spectrum at 4.5 km from Saturn V MLV launch (32 million lb thrust). (Wilhold et al., 1970)

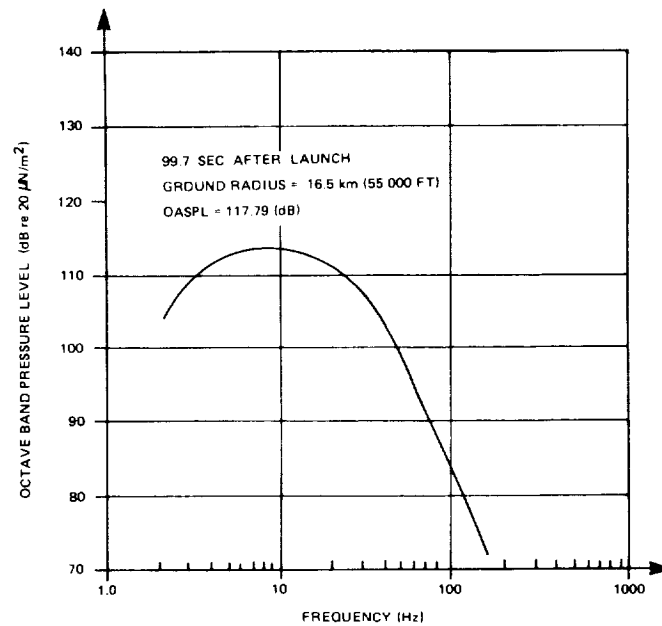


Figure 15-4. Predicted octave band pressure level spectrum at 16.5 km from Saturn V MLV launch (32 million lb thrust). (Wilhold et al., 1970)

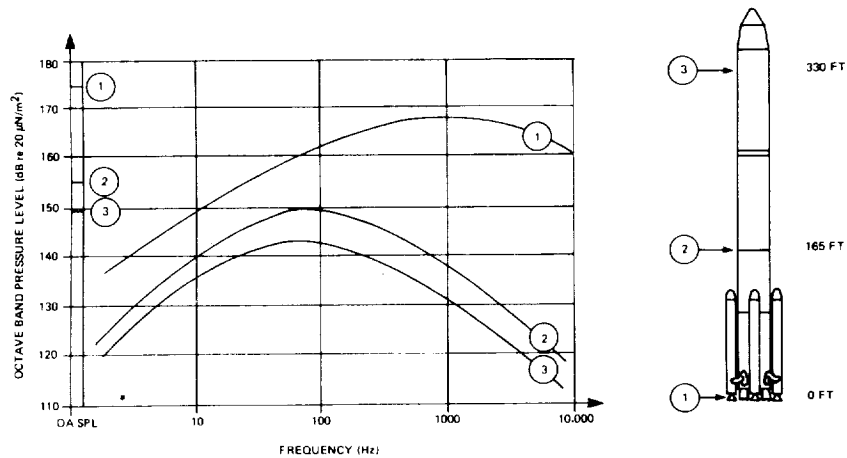


Figure 15-5. Predicted spectra for 3 vehicle stations for a 13.1 million lb thrust configuration. (Saturn V with four 1.4 million lb thrust strap-on units.) (Wilhold et al., 1970)

### Apollo Launch Noise

Detailed measurements of Apollo launch noise have been made at many positions in and around Cape Kennedy Launch Complex 39A. The range of octave-band SPL around the vehicle at a distance of 400 meters is shown in table 15-2. Also shown are the maximum levels achieved on the side of the gantry closest to the rocket 10 m above ground.

Table 15-2  
Octave Band Pressure Levels Around an Apollo Launch  
at a Distance of 400 Meters and on the Gantry 10 Meters Above Ground

| Center Frequency (Hz) | Sound Pressure Level (dB)* |               |
|-----------------------|----------------------------|---------------|
|                       | At 400 Meters              | On the Gantry |
| 2                     | 122 - 143                  | 158           |
| 4                     | 136 - 155                  | 163           |
| 8                     | 141 - 157                  | 162           |
| 16                    | 136 - 158                  | 159           |
| 31                    | 135 - 158                  | 159           |
| 63                    | 130 - 152                  | 164           |
| 125                   | 129 - 149                  | 166           |
| 250                   | 127 - 146                  | 168           |
| 500                   | 125 - 142                  | 164           |
| 1000                  | 120 - 139                  | 161           |
| 2000                  | 116 - 138                  | 158           |
| 4000                  | 118 - 136                  | 156           |
| 8000                  | 110 - 131                  | 152           |

\*re  $20 \mu\text{N/m}^2$ .

(J.F. Kennedy Space Center, 1969a)

The SPL to which the Apollo astronauts are exposed remains above 85 dB for about 80 seconds during liftoff (French, 1967). The maximum SPL achieved at the crew position is shown in table 15-3. Since the crew will be wearing helmets and space suits during launch, a conservative estimate of the actual SPL at the ear is also shown in table 15-3.

It is important to note that the maximum SPL for the Apollo system occurs at very low frequencies, below 100 Hz. This noise, which is produced by the turbulent mixing of the booster propulsive flow with the surrounding atmosphere, will continue to become higher in intensity, and lower in frequency, as boosters increase in size and thrust. The very large boosters, such as Nova, will probably produce their maximum noise energy in the infrasonic region (below 20 Hz) (National Aeronautics and Space Administration, Marshall Space Flight Center, 1961).

Table 15--3  
Sound Pressure Level in Crew Area and at Ear Position  
of Apollo Astronauts at T + 60 Seconds

| Center Frequency (Hz) | Sound Pressure Level (dB) |              |
|-----------------------|---------------------------|--------------|
|                       | Crew Area                 | Ear Position |
| 63                    | 123                       | 119          |
| 125                   | 123                       | 116          |
| 250                   | 126                       | 112          |
| 500                   | 125                       | 106          |
| 1000                  | 123                       | 96           |
| 2000                  | 120                       | 89           |

(French, 1967)

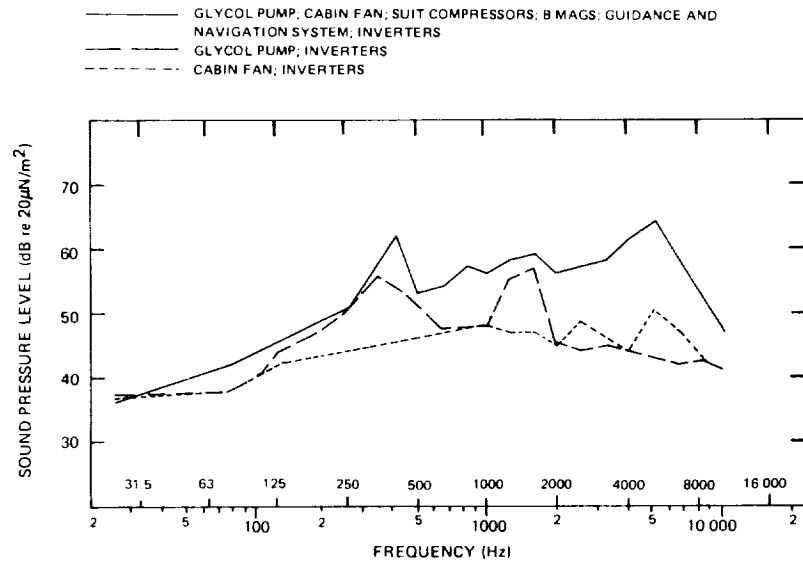
Low-frequency sounds must be measured accurately so research may be continued on the effects of these sounds on man. Hearing protective devices, such as helmets and circumaural muffs, provide their poorest protection at low frequencies (discussed further in a later section), so research must be continued on providing more efficient means of protecting man from the possible damaging effects of low-frequency sound. Also, as was discussed in the section on propagation of sound, low-frequency energy is least affected by excess attenuation. Therefore, these are the frequencies which are most likely to produce both physical and psychological effects in the communities surrounding launch areas.

#### Spacecraft Noise Levels During Non-Powered Flight

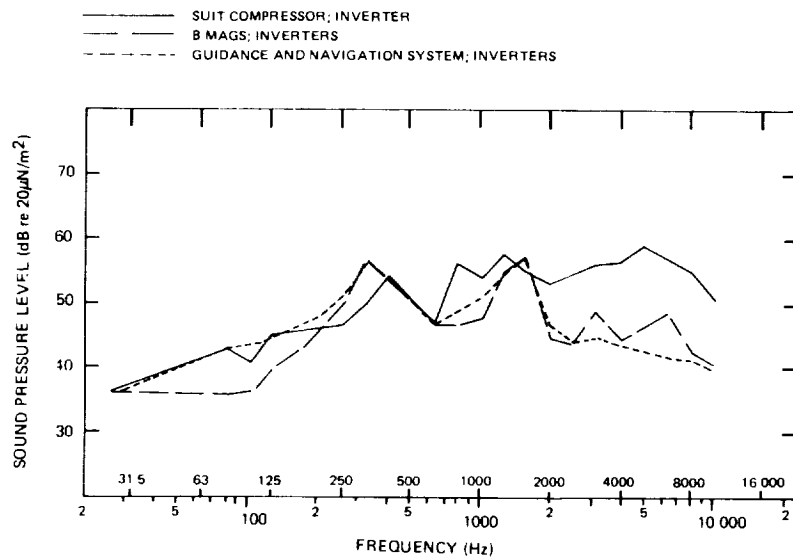
Apollo crew compartment noise measurements are shown in figure 15-6 for non-powered flight. These data were acquired in the 2TV-1 command module which was used for combined thermal/vacuum tests at the NASA Marshall Space Flight Center (MSFC) facility. Measurements were made with the internal environment controlled by the spacecraft life support system, and compartment pressure was maintained at about 5 psia. During this simulated flight, the interior noise sources included the glycol pumps, cabin fans, suit compressors, B mags, inverters, and guidance and navigational systems.

#### Effects of Noise and Blast on Hearing

This section treats the factors influencing the acquisition and recovery of hearing loss for steady-state and impulse noise, and for blast (a special case of impulse noise). A basic understanding of the anatomy, physiology and functioning of the human auditory system is assumed. Readers not possessing this background may find a preliminary reading of chapter 14 helpful.



(a) 1/3 octave band pressure level in command module crew area.



(b) 1/3 octave band pressure level in command module crew area.

Figure 15-6. Apollo crew compartment noise.

### Types of Hearing Loss

The sensitivity of human hearing at a particular test frequency is referred to as the threshold of audibility. Thresholds stated with reference to standard criteria [such as ANSI-1951 or ISO-1964 audiometric zero (International Standards Organization)] are called hearing levels *re* the appropriate reference level. When a loss of sensitivity is temporary, i.e., returns to baseline after a suitable recovery interval, it is referred to as a temporary threshold shift, or TTS. A loss of sensitivity which does not return to baseline is called a permanent threshold shift, PTS. TTS is usually measured at 2 minutes or longer after exposure, and is referred to as  $TTS_{2 \text{ min}}$  or, simply,  $TTS_2$ .

### Relation Between TTS and PTS

Some relation is assumed to exist between  $TTS_2$  experienced on a near-daily basis and the likelihood of eventual accumulation of PTS. CHABA (Committee on Hearing, Bioacoustics and Biomechanics) Working Group 46 (1965) assumed that 10 years of near-daily exposure would result in  $PTS_{10 \text{ yr}} = TTS_{2 \text{ min}}$ . TTS measures are widely used in assessing noise effects on hearing because (1) TTS is a valid measure of the temporary effects of noise exposure, and (2) TTS can affect man's ability to perform tasks requiring maximum hearing sensitivity. In fact, where life-or-death decisions rest on the acuteness of man's hearing, as in astronauts' reception of speech signals, or in the perceiving of auditory warning signals, prevention of excessive TTS is the most important consideration. Absence of TTS may be responsible for saving a life or many lives. TTS will be used here as the primary indicant of noise effects on hearing threshold sensitivity.

### Susceptibility to TTS

The concept of susceptibility refers jointly to the fact that for a given noise exposure, different ears demonstrate varying amounts of TTS, and for a given sample of ears, different noise conditions may produce varying distributions of TTS. Because of the unpredictable and uncontrollable variability in ears' responses to noise--between days and among noise conditions--the possibility of developing criteria for protecting *specific* ears from excessive TTS is at best slim (Ward, 1968; Hodge & McCommons, 1966). As a result, criteria for determining what constitutes hazardous vs. nonhazardous noise exposures are, in reality, a form of actuarial or statistical tables in which the responses of certain proportions of noise-exposed populations are predicted.

### Steady Sounds and Noise

*Acquisition of TTS.* The many factors influencing the acquisition of TTS from steady sound and noise exposure have been reviewed by Ward (1963, 1969) and Nakamura (1964). Some of the salient aspects are summarized below. When reading these, it should be kept in mind that the *interaction* of variables is a most important consideration. The present discussion will be limited primarily to TTS measured 2 minutes or longer after exposure.

Stimulus Amplitude.  $TTS_2$  increases linearly with average SPL over the range of 75 to 120 dB and possibly higher. The difference between TTS produced by 85- and 90-dB noise is about the same as the difference between that produced by 90- and 95-dB SPL. This relationship is illustrated in figure 15-7.

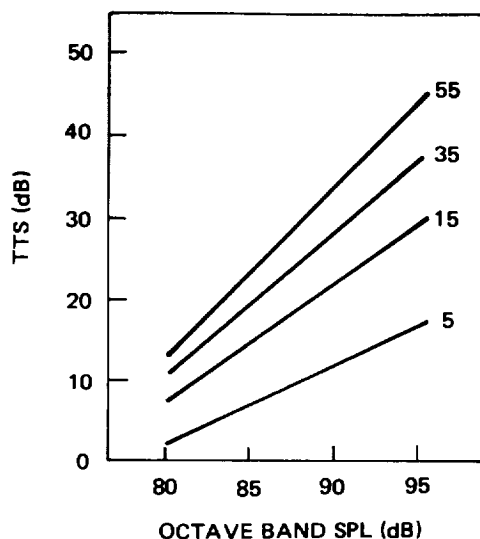


Figure 15-7. TTS at 4 kHz as a function of SPL for exposure to octave band of 2-4 kHz. Parameter is exposure time in minutes. (Shoji et al., 1966)

Exposure Frequency. For equal SPL in octave-bands of noise, low frequencies present less hazard to the ear than higher frequencies up to 4 kHz. This is due to the frequency-response characteristics of man's ear. Figure 15-8 illustrates the general relation between exposure frequency and TTS for octave bands of noise.

Pure tones produce more TTS than corresponding octave bands of noise of the same amplitude. Carter and Kryter (1962) showed that the overall level of an octave band had to be about 5 dB higher than a pure tone at the octave center frequency to produce an equal amount of TTS; this 5 dB correction was later adopted for use in the CHABA (1965) steady-state noise damage-risk criterion.

Cohen and Bauman (1964), investigating TTS from broad-band noise, showed that when pure tones below 2 kHz were present the combined tone and noise condition produced more TTS than noise alone, even though the overall SPLs for the two conditions were equated.

Jerger et al. (1966), and Alford et al. (1966) investigated TTS from infrasonic tones, concluding that the most hazardous conditions were at or above 141 dB SPL in the range of 10 to 12 Hz.

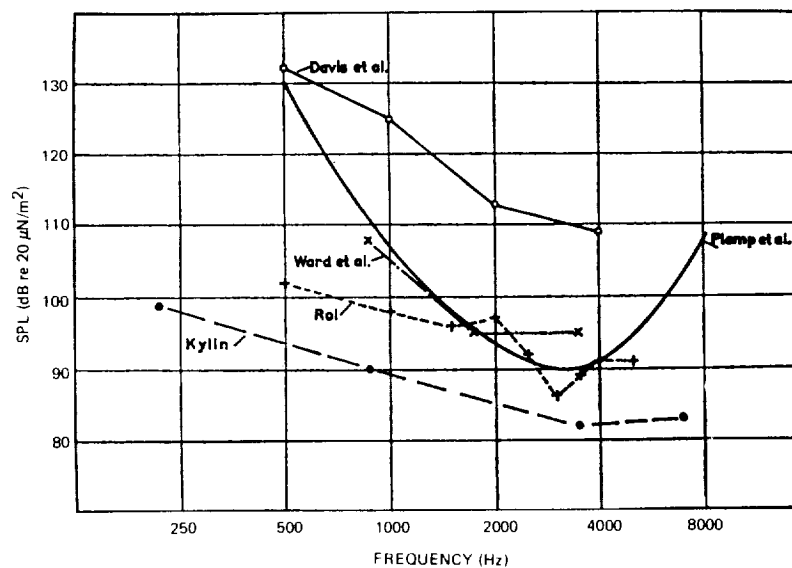


Figure 15-8. Relation between exposure of frequency and TTS for octave bands of noise: comparison of some iso-traumatic lines, all based on TTS. Within any one set of data, the same exposure time or TTS criterion was used. (Plomp et al., 1963)

There is evidence that exposure to ultrasonic tones up to 120 dB SPL is unlikely to produce TTS (Acton & Carson, 1967). No clear evidence exists upon which to assess the effect of higher SPL.

Duration of Exposure. TTS<sub>2</sub> from steady noise grows linearly with the logarithm of exposure time, as illustrated in figure 15-9. Most experiments have involved relatively short exposures ( 8 hr), but Yuganov, et al. (1967) have suggested that the rule is valid for exposure times of up to 720 hours.

The effects of intermittent noise exposure have been reviewed by Ward (1963, 1966) and Cohen and Jackson (1969), and others have compared the effects of continuous and intermittent exposures. In general, intermittent exposures produce less TTS than continuous exposures.

Test Frequency. TTS involves areas, not points, on the basilar membrane (Ward, 1963). Thus, virtually any type of tone or noise exposure affects auditory thresholds at a range of test frequencies. For SPL above 60 dB, maximum TTS occurs at a frequency on the order of one-half to one octave above the stimulating frequency for pure tones and bands of noise. The relative TTS occurring at various frequencies with a broad-band ("white") noise exposure is shown in figure 15-10.

Preexposure Hearing Level. The foregoing discussion has been based almost entirely on ears with *normal* sensitivity. Impaired ears may demonstrate different results. Ears with conductive hearing losses, for



example, would be expected to show less TTS because less energy is transmitted to the cochlea. Ears with pure sense organ losses should also show less TTS than normals, but this is due to their having less remaining sensitivity to lose.

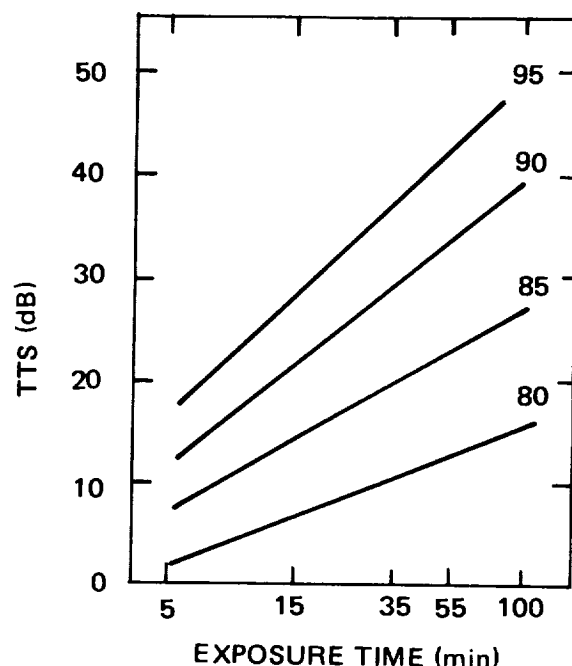


Figure 15-9. TTS at 4 kHz from exposure to 2-4 kHz octave band noise. Parameter is noise level in SPL. (Shoji et al., 1966)

Sex and Age. No systematic difference in TTS as a function of sex and age have been reported (Ward et al., 1959b; Loeb & Fletcher, 1963), nor have any systematic trends in TTS growth been reported solely as a function of age. For a discussion of the PTS which normally accompanies the aging process (presbycusis), see chapter 14.

Monaural vs. Binaural Exposure. Ward (1965) showed that monaural exposures were accompanied in general by about 5 dB more TTS than binaural exposure to the same condition.

Recovery of TTS. When  $TTS_2$  does not exceed about 40 dB, and is induced by relatively short exposures to continuous blocks of steady-state noise, TTS recovers linearly in log time and occurs within a maximum of 16 to 48 hours (Ward, 1963; Smith & Loeb, 1969). Under these conditions recovery rate is also independent of test frequency. The slope of the recovery function may, however, vary as a function of the amount of  $TTS_2$ . Representative recovery functions are shown in figure 15-11.

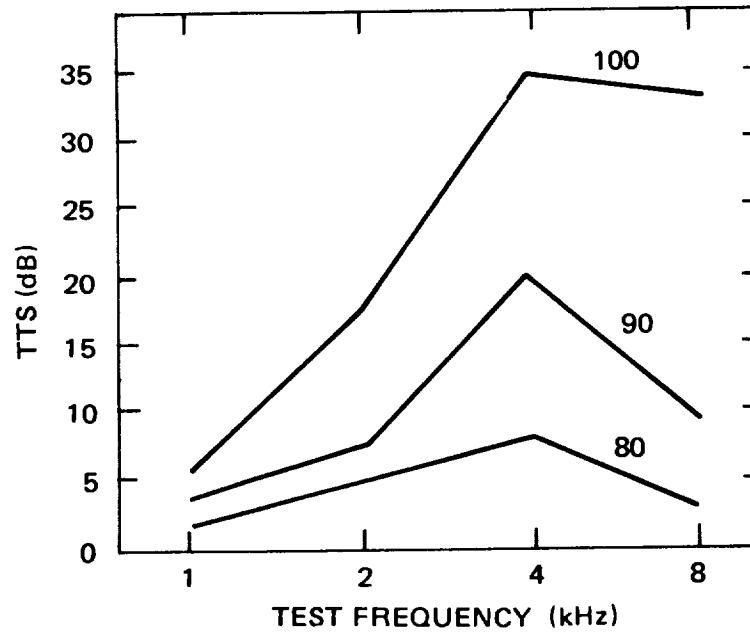


Figure 15-10. Distribution of TTS resulting from 5-min exposure to broad-band noise. Parameter is amplitude in sensation level. (Nakamura, 1964)

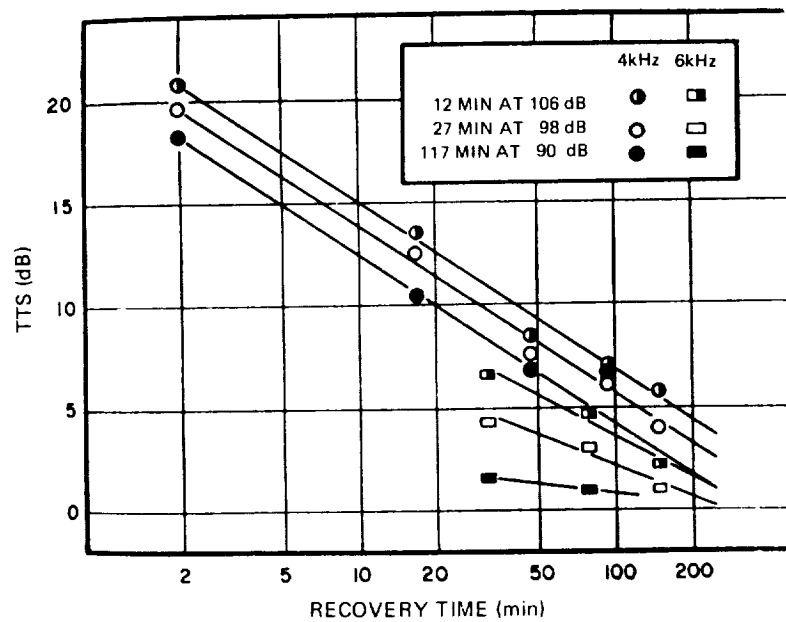


Figure 15-11. Course of recovery at 4 and 6 kHz following 3 different exposures to 1.2 - 2.4 kHz octave band noise. (Ward et al., 1959a)

Since subsequent recovery is usually quite predictable once the value of  $TTS_2$  is known, generalized recovery functions can be developed for  $TTS_H 40$  dB. Such functions permit TTS measured at various times after exposure to be converted backward or forward to  $TTS_2$  for purposes of direct comparison. Kryter (1963) published such a graph for converting  $TTS_t$  to  $TTS_2$  as shown in figure 15-12.

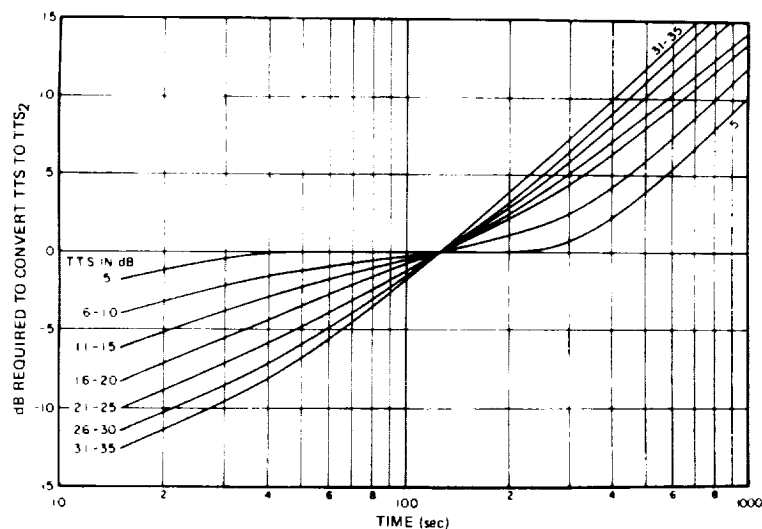


Figure 15-12. Graph for conversion of TTS to  $TTS_2$  with TTS as the parameter. Example: for TTS of 25 dB measured 500 sec after exposure, add 10 dB to arrive at  $TTS_2 = 35$  dB. Graph is based on exposure of subjects to continuous periods of steady-state noise, and is probably invalid for application to TTS induced by other types of exposures. (Kryter, 1963)

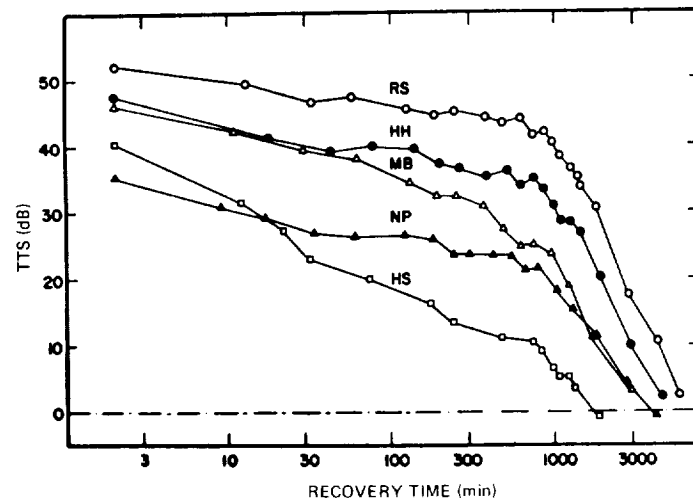
When TTS is induced by exposures to steady noise longer than 8 hours, or by intermittent noise, these generalized recovery functions are probably invalid. Ward (1970) found that intermittent noise caused a significant increase in recovery time, for equal TTS, and Yuganov et al. (1967) and Mills et al. (1970) reported similar findings for exposures of 12 to 720 hours.

As  $TTS_2$  exceeds about 40 dB a change in the recovery function may be noted. Recovery from high values of TTS is linear in time, rather than linear in log time, as illustrated in figure 15-13.

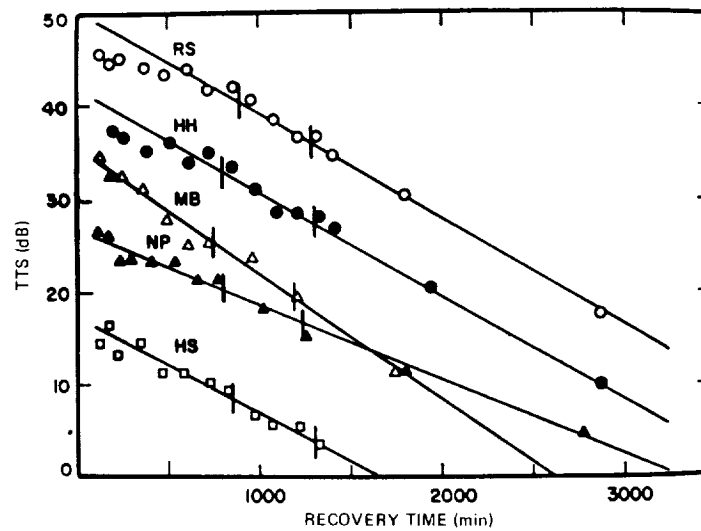
### Impulse Noise

An impulse may be defined as an aperiodic pressure phenomenon of less than 1000 msec duration, having a fast rise time and a peak-to-RMS ratio greater than 10 dB. Such a definition leaves much to be desired, including a 'gray' area of pressure phenomena which may be considered either as long impulses or short, steady sounds. Impulses are, however, characteristic of many working

environments, and common examples include the sound of gunfire, impact and power-operated tools, drop forges, pile drivers, etc.



(a)



(b)

Figure 15-13. (a) Average course of recovery at 3 and 4 kHz following exposure to 105 dB SPL 1.2–2.4 kHz noise whose duration was sufficient to produce 50 dB TTS<sub>2</sub>. Time is represented logarithmically. (b) Data replotted in terms of time, rather than log time (abscissa). (Ward, 1960)

The literature on impulse noise effects has been reviewed by Ward (1963), Chaillet et al. (1964), Coles et al. (1967, 1968), and Rice (1968). Some of the more important findings are summarized below. As was the case with steady noise, the interaction of variables is an extremely important consideration.

#### *Acquisition of TTS.*

**Peak Pressure Level.** The higher the peak pressure level, the greater is the risk of TTS, other parameters being equal. This relation is illustrated in figure 15-14 by data from the classic studies of Murray and Reid (1946), and in figure 15-15 by data from Ward et al. (1961). The peak pressure level where TTS is first produced depends in part on other parameters such as impulse duration or the number of impulses presented, as well as on individual susceptibility.

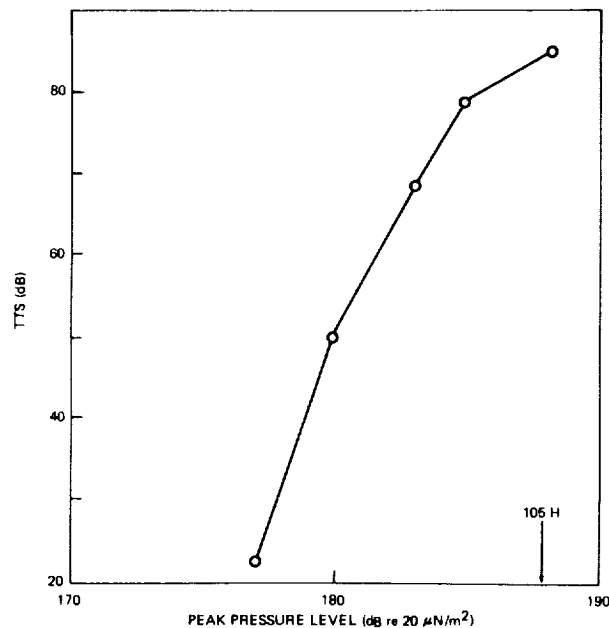


Figure 15-14. TTS as a function of peak pressure level for ears exposed to 10 impulses produced by various weapons. Notation "105 H" on abscissa indicates peak pressure level found in crew area of a current Army howitzer. Graph underscores need for protection of personnel exposed to high noise levels. (Murray & Reid, 1946)

**Impulse Duration.** Fletcher and Loeb (1967) have shown that, for a peak level of 166 dB, 10 to 25 impulses of 92  $\mu\text{sec}$  duration had about the same effect as 75 to 100 impulses of 36  $\mu\text{sec}$  duration. Similar results were later obtained by the same investigators (1968). Acton et al. (1966) showed that 0.22 caliber rifles fired in the open (short duration) did not constitute a hazard to hearing, whereas the same rifles fired in an indoor reverberant range (long duration) did constitute a borderline hazard. The relation between impulse

duration and risk of TTS is best described by reference to the CHABA damage-risk criterion for impulse-noise exposure (discussed later).

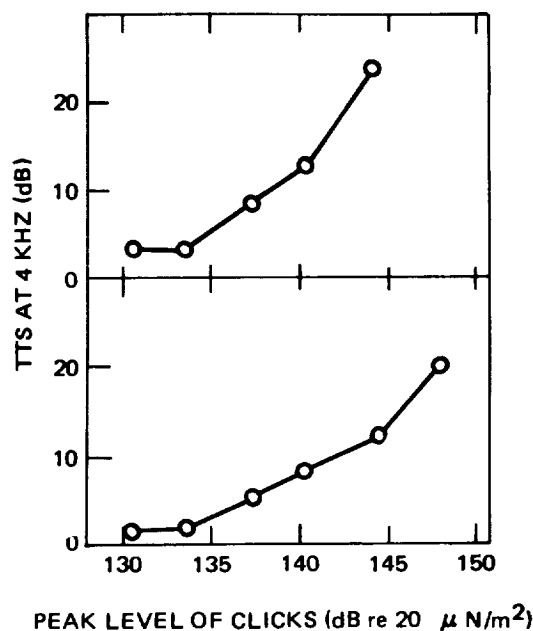


Figure 15-15. TTS at 4 kHz as a function of peak level of clicks. Upper curve: 3 min exposure at 25 clicks/min. Lower curve: 1 min exposure at 25 clicks/min. (Ward et al., 1961)

**Rise Time.** Many impulses have rise times less than 1  $\mu$ sec since a shock wave is a major component of the event. To date, however, no serious attempt has been made to relate impulse rise time to the risk of TTS, and this variable is not treated systematically in damage-risk criteria.

**Spectrum.** Recently it has become possible to perform spectral analyses of impulses with a computer (Pease, 1967). There are, however, few data relating the spectrum of impulses to risk of TTS, and considerably more investigation will be required before such information will be of any real benefit.

**Number of Impulses.** TTS appears to grow linearly with the number of impulses, or linearly in time for a constant rate of presentation, as illustrated in figure 15-16.

**Rate of Impulse Presentation.** TTS growth rate from impulses does not differ significantly when the inter-pulse interval is between one and 9 seconds. At less than one second between pulses, TTS growth rate is reduced because of the protective action of the aural reflex. Also, when as much as 30 seconds elapses between successive impulses, TTS grows more

slowly because of the recovery which takes place between impulses (Ward, 1962; Ward et al., 1961).

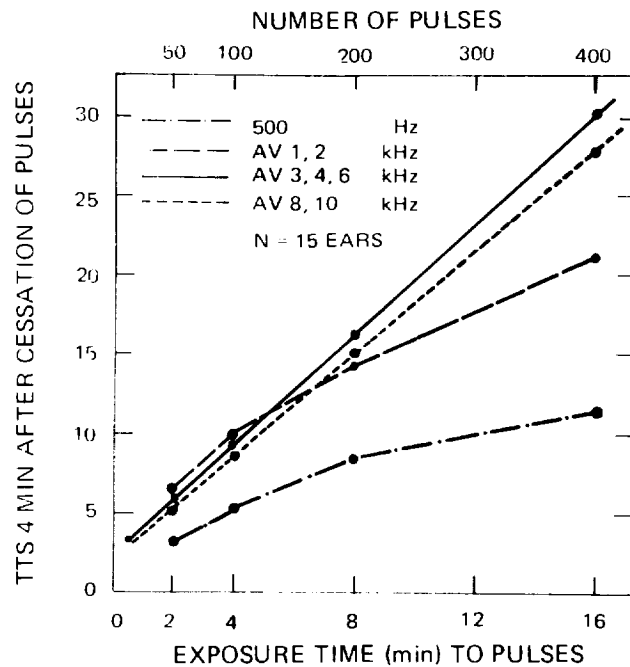


Figure 15-16. Average growth of TTS from pulses as a function of exposure time (lower abscissa), or of number of pulses (upper abscissa) when pulses are presented at a constant rate. TTS from impulses increases linearly with time or with number of pulses. (Ward et al., 1961)

**Ear Orientation.** When the impulse noise includes a shock wave, the orientation of the external ear with respect to the shock front is of considerable importance. Hodge et al. (1964) showed that when the ear is at normal incidence to the shock wave, the TTS produced is approximately equivalent to that produced by an impulse having 5 dB greater amplitude but arriving at grazing incidence. Golden and Clare (1965) reported a similar difference. Hodge and McCommons (1967b) have also shown that when the shockwave strikes one ear at normal incidence, the other ear, which is shadowed (protected) by the head, evidences considerably less TTS. This explains why it is usually found that right-handed rifle shooters demonstrate more TTS in the left, than right, ear: the right ear is at least partially protected by the head's shadow.

**Test Frequency.** TTS from impulse-noise exposure occurs at a wide range of frequencies, with the maximum TTS usually occurring in the region of 4 to 6 kHz. This effect is illustrated in figure 15-17. Note that whereas mean and median TTS was between 0 and +10 dB at all frequencies, the *range* of

effect was from -25 dB (sensitization) at 3 kHz to +55 dB (loss) at 4 kHz. Also note that this exposure produced TTS at frequencies up to 18 kHz. Loeb and Fletcher (1968) believe that high-frequency TTS is a precursor of speech range TTS, and they suggest that when speech range TTS exceeds the CHABA (1968) allowable limits there is a chance of producing permanent high-frequency hearing loss

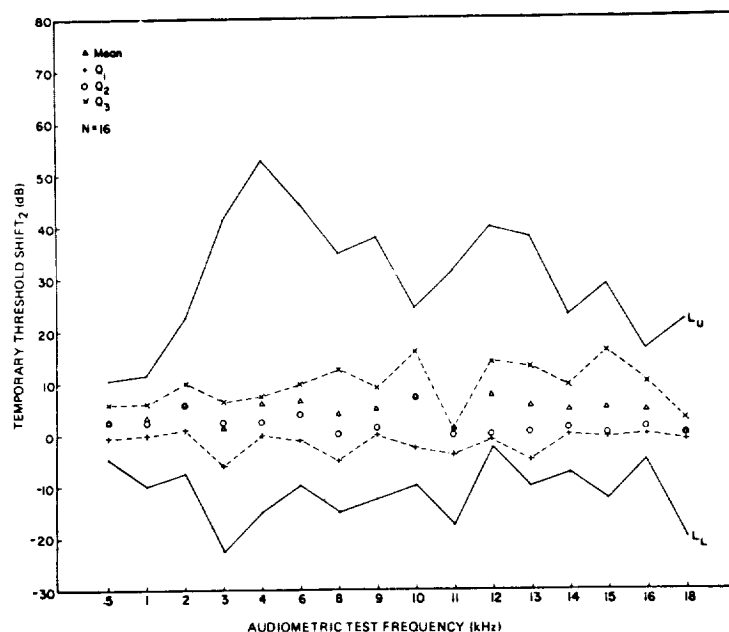


Figure 15-17. Distributions of  $TTS_2$  following exposure to 25 gunfire impulses. (Hodge & McCommons, 1966)

**Monaural vs. Binaural Exposure.** Hodge and McCommons (1967a) found that, on the average, TTS growth rates for binaural and monaural exposure did not differ significantly when the interpulse interval was 2 seconds. There were large individual differences among the subjects, but no consistent trend favoring either type of exposure.

**Recovery of TTS.** A growing body of data indicates that recovery from TTS induced by various types of intermittent noise differs radically from that caused by steady noise exposure. Rice and Coles (1965) observed instances of individual subjects with  $TTS_2 \approx 25$  dB who showed little or no recovery for periods of up to one hour after exposure, but thereafter recovery became approximately linear in log time. Luz and Hodge (1971) have found four types of recovery curves for impulse-noise-induced TTS in humans and monkeys: (1) recovery linear in log time; (2) no apparent recovery for periods of up to one hour, followed by linear in log time recovery; (3) slight recovery followed by an *increase* in TTS; and (4) slight recovery followed by a long plateau of no change, and then further recovery. These diverse functions occur to TTS 30 dB in humans, and suggest



that considerable further research will be required to derive averaged, generalized recovery functions for impulse noise induced TTS.

For TTS<sub>2</sub> 40 dB recovery may be very slow; Fletcher and Cairns (1967) suggest that 6 months of recovery may be necessary to accurately assess residual PTS from excessive exposure to gunfire noise.

### **Blast**

Blast differs little from impulse noise so far as the hearing mechanism is concerned. The term "blast" is typically used to refer to much higher pressures and/or longer durations than are usually associated with common impulse-noise sources. However, so far as the development of TTS is concerned, the preceding discussion of impulse-noise parameters is equally applicable to the parameters of blast.

Single, large-amplitude blast waves may rupture the eardrum. The threshold for eardrum rupture is about 5 psi; at 15 psi 50 percent of eardrums will probably be ruptured (Hirsch, 1966). When the eardrum is ruptured loss of hearing is severe in the affected ear, although after healing (2 to 6 weeks), the ear's sensitivity may return to normal, particularly if the middle ear ossicles are intact (Hamberger & Liden, 1951; Akiyoshi et al., 1966). Rupture of the eardrum thus serves as a "safety valve." If the eardrum is not ruptured by the blast, profound PTS may result from a single exposure, particularly at the higher frequencies of hearing (Ward & Glorig, 1961; Singh & Ahluwalia, 1968).

### **Long-Term Exposure to Spacecraft Noise**

Short-term exposure to the high level, low frequency noise of spacecraft launch will not likely adversely affect astronauts, especially when earmuffs, helmets, and other protective gear are worn (Mohr et al., 1965). On the other hand, the relatively lower level steady background noise to which they will be exposed could adversely affect astronauts' hearing. Such background noise is produced by the life support system and other items of onboard equipment, such as glycol pumps, cabin fans, suit compressors, guidance and navigation systems, and inverters.

Yuganov et al. (1967) reported an extensive series of studies of the effects of spacecraft background noise on hearing. Their studies were conducted in a simulated spacecraft environment (complete with confinement and hypoactivity) during ground static testing. Figure 15-18 illustrates the growth of TTS resulting from successively longer exposures to 75 dB levels.\* Yuganov et al. reported that recovery time for noise-induced TTS became progressively longer with increased exposure time. This phenomenon has been verified by NASA-sponsored studies conducted under the Gemini program, and was also reported by Mills et al. (1970).

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\*Although it is not clearly stated in their report, it is assumed from the description of procedure and instrumentation that the noise levels stated refer to dBA.

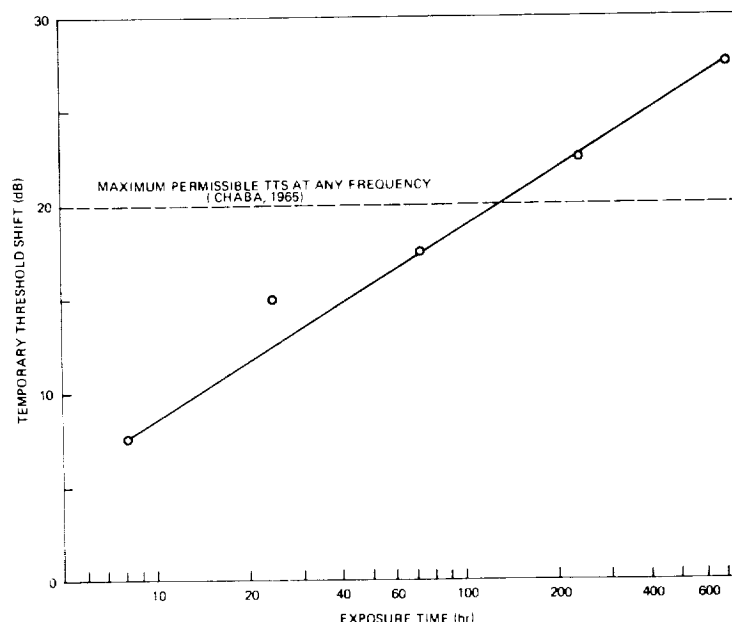


Figure 15-18. Growth of TTS with time for overall exposure level of 75 dB. Growth rate was linear in log time, and compares favorably with other data for higher levels and shorter durations (see figures 15-8 and 15-10). CHABA (1965) limit of 20 dB maximum TTS at any frequency was exceeded at about 130 hr exposure. (Yuganov et al., 1967)

In followup studies with 60 to 65 dB noise levels, Yuganov et al. found no evidence of TTS (or behavioral or physiological alterations) in astronauts exposed up to 60 days (1440 hours). Thus these authors concluded, and recommended, that for extended space flights of up to 60 days the background noise levels inside spacecraft should not exceed 65 dB. The 65 dB overall background noise limit recommendation compares favorably with the design criterion for background noise for Apollo spacecraft, indicated by Dr. B. O. French of the Manned Spacecraft Center (personal communication) to be NC-55, or approximately 60 dBA.

### Effects of Hearing Loss on Performance

Some persons are likely to suffer TTS or PTS from noise exposure in spite of the application of safety criteria or the use of protective equipment. Other persons may have PTS from disease or trauma. Accordingly, in this section the effects of TTS and PTS on performance will be briefly considered.

### Detection of Low-Level Sounds

Earlier, it was noted that an ear's threshold sensitivity (hearing level) is stated with reference to audiometric zero, such as the ANSI-1951 or ISO-1964 values. Audiometric zero at various test frequencies represents the lowest SPL

which can be detected, on the average, by listeners having "normal" hearing. Table 15-4 shows the SPL representing ISO-1964 audiometric zero at selected frequencies and the "allowable TTS" permitted by the CHABA (1965, 1968) damage-risk criteria for steady and impulse noise. The column at the far right shows the minimum SPL detectable, on the average, by a listener whose baseline hearing sensitivity equals ISO audiometric zero and who has CHABA-limit TTS at the various frequencies. These values are also descriptive of the detection limits for a listener who has PTS of the amounts shown in column 3.

Table 15-4  
SPL Representing ISO Audiometric Zero and Minimum Detectable  
SPL for a Listener Having CHABA-Limit TTS

| Frequency<br>(Hz) | SPL for ISO Zero<br>(dB re 20 $\mu$ N/m <sup>2</sup> ) | CHABA Allowable<br>TTS (dB) | Minimum Detectable SPL<br>(dB re 20 $\mu$ N/m <sup>2</sup> )* |
|-------------------|--------------------------------------------------------|-----------------------------|---------------------------------------------------------------|
| 500               | 11                                                     | 10                          | 21                                                            |
| 1000              | 6.5                                                    | 10                          | 16.5                                                          |
| 2000              | 8.5                                                    | 15                          | 23.5                                                          |
| 3000              | 7.5                                                    | 20                          | 27.5                                                          |
| 4000              | 9                                                      | 20                          | 29                                                            |
| 6000              | 8                                                      | 20                          | 28                                                            |
| 8000              | 9.5                                                    | 20                          | 29.5                                                          |

\*This interpretation assumes that the listener's preexposure hearing sensitivity was equal to ISO audiometric zero.

Given a knowledge of the spectral characteristics of a low-level sound which must be detected, and the lowest SPL at various test frequencies which a particular listener can detect, predictions can be made of the listener's ability to detect the low-level sound. A convenient example from a military context, well-known to the authors, may be cited. It has been shown that sounds created by people walking over various types of terrain contain energy primarily in the 3 to 8 kHz range. Knowing this, it would be hypothesized that persons having TTS or PTS in this range of frequencies would be less able to detect such sounds than persons with normal hearing sensitivity. This hypothesis has been confirmed by experimental test, and these results suggest that, for example, military personnel receiving TTS from daytime exposure to weapon noise should not be assigned nighttime duty as perimeter sentry where the preservation of a life, or many lives, may depend on maximum hearing sensitivity, unimpaired by slowly-recovering TTS. These results further suggest that in *any* detection situation the listeners selected should have the most sensitive hearing possible, free of TTS or PTS.

### Reception of Speech

The spectral characteristics of speech must be considered in assessing the effects of TTS or PTS on speech reception. Speech sounds range in frequency from 0.2 to 7 kHz; peak energy occurs at about 0.5 kHz. Speech sounds are of two basic types: vowels and consonants. Vowel sounds fall roughly into the frequencies below 1.5 kHz, and consonants are above 1.5 kHz (Sataloff, 1966). Vowels are thus more powerful (i.e., contain more energy) than consonants. Vowel sounds indicate that someone is saying something, but consonants aid in discriminating what is being said. Thus, consonants may be said to convey more information than vowels.

A person with TTS or PTS in the range of 0.2 to 1.5 kHz has difficulty hearing speech unless it is quite loud, and is unable to hear soft voices. If the talker raises his voice level the listener will be able to understand what is being said.

The person with TTS or PTS in the range of 1.5 to 7 kHz, on the other hand, hears vowels normally but finds it difficult to discriminate consonants. Increasing the speech level aids little, but careful enunciation by the talker is of great benefit. This type of TTS or PTS is a particularly severe problem in occupational deafness since the loss of hearing sensitivity frequently occurs first in the 3 to 6 kHz range. The problem is compounded by the presence of background masking noise, since the low-level consonant sounds are masked to a greater extent by broad-band noise than the higher-level vowel sounds. This fact has led some hearing conservation groups to develop criteria for protecting hearing at frequencies up to 4 kHz (e.g., Piesse et al., 1962). In the United States, however, this has not been done: only frequencies of 0.5 to 2 kHz are considered in assessing occupational hearing impairment (Bonney, 1966).

Table 15-5 shows classes of hearing handicap which are defined by the average of PTS at 0.5, 1, and 2 kHz, as recommended by the Committee on Conservation of Hearing (1969). In general it may be said that TTS of the same amount will constitute an equivalent degree of impairment, although of course the impairment disappears when the individual has recovered from the TTS.

### Subjective and Behavioral Responses to Noise Exposure

An earlier section considered the effects of noise demonstrated after exposure and indicative of a decrease in the responsiveness or neural activity in the auditory receptors. In this section, by contrast, noise effects which occur currently with exposure and result in increased neural activity will be considered. These responses will be discussed in terms of (1) general observations, (2) masking of auditory signals, (3) masking of speech, and (4) annoyance. Methods for measuring speech intelligibility and assessing the effect of noise on speech intelligibility will be presented. The treatment of annoyance will introduce the notion of "community response" to noise exposure.

Table 15-5  
Chart for Determining Class of Hearing Impairment

| Class | Degree of Handicap | Average Hearing Level (dB re ISO 1964)<br>at 500, 1000, and 2000 Hz in Better Ear* |           | Ability to Understand<br>Ordinary Speech        |
|-------|--------------------|------------------------------------------------------------------------------------|-----------|-------------------------------------------------|
|       |                    | At Least                                                                           | Less Than |                                                 |
| A     | Not significant    |                                                                                    | 25        | No significant difficulty with faint speech     |
| B     | Slight             | 25                                                                                 | 40        | Difficulty with faint speech only               |
| C     | Mild               | 40                                                                                 | 55        | Frequent difficulty with normal speech          |
| D     | Marked             | 55                                                                                 | 70        | Frequent difficulty with loud speech            |
| E     | Severe             | 70                                                                                 | 90        | Can understand only shouted or amplified speech |
| F     | Extreme            | 90                                                                                 |           | Usually cannot understand even amplified speech |

\*If average of poorer ear is 25 dB or more greater than that for better ear, add 5 dB to average for better ear.  
(Committee on Conservation of Hearing, 1969, p. 43)

### General Observations

Broadbent and Burns (1965) and Cohen (1969) have reviewed the effects of noise on behavior and psychological state. In some respects the existing literature does not yet support firm conclusions, but representative subjective and behavioral responses are summarized in table 15-6.

### Masking of Auditory Signals

The amount of masking is the number of decibels that the quiet threshold of a signal must be raised to be intelligible because of the presence of masking sound. Masking effects may be classed as monaural or interaural. Monaural masking occurs when the signal and noise reach the ear(s) at the same time; this type of masking is most critical in working environments where personnel are not wearing earphones, and will be discussed below. (Interaural masking occurs when the signal reaches one ear and noise the other ear. No interaural masking occurs unless the noise exceeds about 40 to 50 dB SPL, since below this level the listener can readily distinguish between the sounds heard separately in his two ears. At higher levels the noise is transmitted to the "signal" ear via bone conduction; thus this situation may be regarded as a special case of monaural masking with the head serving as an attenuator. Interaural masking is a particular problem when the telephone is used in a noisy environment, and when the SPL in one ear is much higher than in the other.)

The monaural masking effect of a pure tone, or of a noise having a strong pure tone component, is greatest near the frequency of the tone but also extends to frequencies adjacent to the masking tone. Curves of masking effects as a function of frequency are shown in figure 15-19. Audible beats near the frequency of the masking tone increase the audibility of the signal and thus reduce the degree of masking at these frequencies. For tones of low intensity masking is confined to a region near the masking tone; for higher intensities the masking is extended, particularly at frequencies above the masking tone. The masking effect of narrow-band noise is quite similar to that for pure tones, except that the dips due to audible beats are absent. Masking of signals by wide-band noise whose level does not exceed about 60 to 70 dB SPL is governed by the critical band concept. At low noise levels pure tones are masked by only a narrow range of frequencies whose width defines the critical band for that signal frequency. The width of the critical band varies from about 40 to 200 Hz, over the tonal range of 0.5 to 8 kHz. Within this range, and for low noise levels, an increase of 10 dB in noise level results in about 10 dB additional masking of tones within the critical band. Above masking levels of about 70 dB SPL, however the width of the critical band increases markedly in both directions. A 10 dB increase in noise level will still cause about 10 dB more masking of frequencies within the noise band, but it may also increase the masking effect at more distant frequencies by as much as 20 dB.

Table 15-6  
Representative Subjective and Behavioral Responses to Noise Exposure

| Conditions of Exposure |                                |              | Reported Disturbances                                                                    | Reference               |
|------------------------|--------------------------------|--------------|------------------------------------------------------------------------------------------|-------------------------|
| SPL (dB)               | Spectrum                       | Duration     |                                                                                          |                         |
| 150*                   | 1 – 100 Hz                     | 2 min        | Reduced visual acuity; chest wall vibrations; gag sensations; respiratory rhythm changes | Mohr et al., 1965       |
| 120                    | Broadband                      | 8 hr         | Reduced ability to balance on a thin rail                                                | Nixon et al., 1966      |
| 110                    | Machinery noise                |              | Chronic fatigue                                                                          | Cohen, 1969             |
| 105                    | Aircraft engine noise          |              | Reduced visual acuity, stereoscopic acuity, near-point accommodation                     | Panian, 1963            |
| 90                     | Broadband                      | Continuous   | Vigilance decrement; altered thought processes; interference with mental work            | Broadbent & Burns, 1965 |
| 85                     | 1/3-octave @ 16 kHz            | Continuous   | Fatigue, nausea, headache                                                                | Acton, 1968             |
| 75                     | Background noise in spacecraft | 10 – 30 days | Degraded astronauts' performance                                                         | Yuganov et al., 1967    |
| 60                     | SIL                            | 80 sec/hr    | Annoyance reactions in 50% of community residents                                        | Borsky, 1958            |

\*In this study subjects wore protective devices to prevent hearing loss.

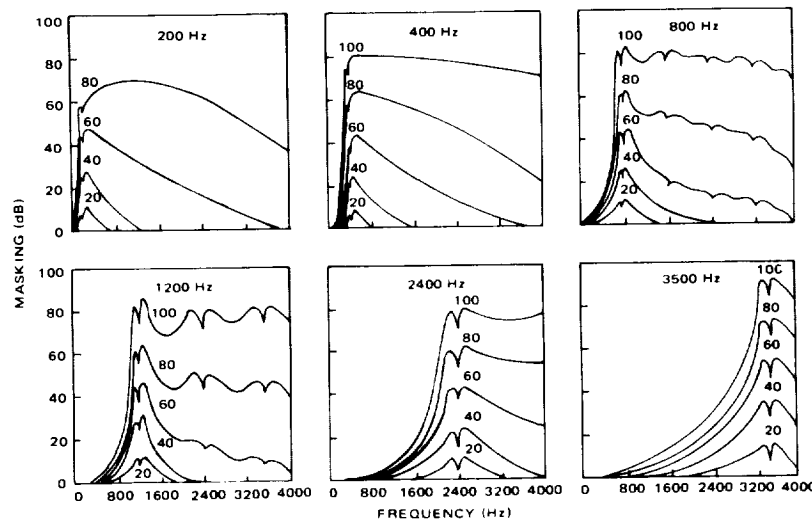


Figure 15-19. Masking as a function of frequency for masking by pure tones of various frequencies and levels. Number at top of each graph is frequency of masking tone. Number on each curve is level above threshold of masking tone. (Wegel & Lane, 1924)

### Masking of Speech by Noise

Most of the energy required for near-perfect speech intelligibility is contained in the range of 0.2 to 7 kHz. This range may be narrowed to 0.3 to 4.5 kHz without significant loss in intelligibility. (In reducing the frequency range it must be remembered that 1.5 kHz constitutes the "center of importance" of speech, and narrowed pass bands of a communications system should be centered on about 1.5 kHz.) Consonants contain energy at frequencies above 1.5 kHz, whereas vowels contain lower-frequency energy. Unfortunately, the consonants, which convey most of the information in English speech, contain very little energy. Thus, they are more subject to interference (masking) from noise than are vowels. Conversely, vowels contain more energy but transmit less information.

*Communication System Design.* It is desirable to maintain as high a speech signal-to-noise ratio as possible in each frequency band, with particular emphasis on those bands which contribute most to intelligibility. Another consideration is the point of overload of the hearing mechanism: the level above which intelligence is no longer extracted from the stimulus. The overload effect can be demonstrated quite readily in a noisy environment when a voice comes over a loudspeaker at a very high level. A listener will find the amplified speech more intelligible when his ears are plugged than when listening without earplugs. This effect occurs because with the ears plugged the speech signal does not overload the hearing mechanism and, at the same time, the signal-to-noise ratio remains constant. Overloading of the ear due to speech amplitude begins to occur when the overall RMS level of the speech signal is about 100 dB at the listener's ear. (The average overall RMS level of speech in a quiet environment may be



approximated by subtracting 3 dB from the arithmetic average of the peak levels observed on a sound level meter set for slow meter damping on the C-scale.) In addition to not contributing to intelligibility, higher levels of speech signals produce discomfort and possible hearing loss.

*Factors in Speech Intelligibility.* Two types of communications must be considered in discussing speech intelligibility: electrically-aided, and direct. The effectiveness of both types of voice communication are determined by the following parameters: (1) level and spectrum of ambient noise at the ear (includes both acoustical noise, and electronically-induced noise); (2) voice level and spectrum of speech; (3) distance between the speech source and the listener's ear; and (4) the complexity and number of alternative messages available to the listener. Electrically-aided speech more specifically also depends upon the characteristics of all of the components of the transmission and receiving systems.

*Recommended Approaches to Measurement of Speech Intelligibility.* Speech intelligibility is measured by determining the percentage of words correctly received by listeners. This may be done by conducting subjective tests with talkers and listeners, or by calculations based on the signal-to-noise ratio in various frequency bands. The choice of approach will be determined by the amount of time, personnel and/or instrumentation available.

PB Word Intelligibility Test. In the bioastronautics field one usually attempts to discriminate among, or evaluate, highly effective communications systems. This requires a sensitive test of speech intelligibility—one that is capable of detecting small differences between systems. Therefore, the use of the "Phonetically Balanced (PB) Monosyllabic Word Intelligibility Test" (ANSI Standard S3.2-1960) is recommended for applications requiring maximum accuracy.

Some aspects of the test procedure are as follows. The test material consists of 20 lists of 50 phonetically-balanced words each. Each list is of approximately the same difficulty. The talker reads the words in a "carrier sentence" at 4-second intervals and the listener writes down each key word. The hearing level of both talkers and listeners must average no more than 10 dB overall, with no more than 15 dB at any of the frequencies 0.25, 0.5, 1, 2, and 4 kHz (re ANSI Standard Z24.5-1951). Talkers must have no obvious speech defects or strong regional or national accents. Test personnel must be completely familiar with each of the 1000 words and with the speech characteristics of the talkers. The test must always be given in its entirety (i.e., all 1000 words must be used), and if the test is to be repeated several times with the same personnel, it is recommended that the order of words within lists be randomized for each presentation. Normally, 8 to 10 hours of talker and listener training are required to properly utilize the PB intelligibility test.

PB intelligibility score may be acceptable in certain instances with values as low as 50 percent (of words correctly received). Only rarely is an intelligibility score of 90 percent required. Single digits may be transmitted with greater than 99 percent reliability with a system providing a PB score of 60 to 70 percent,

since the listener has only 10 alternatives from which to choose. The criterion of acceptability for communication systems should be a *mandatory score of 70 percent* and a *desirable score of 80 percent* when the ANSI PB method is followed.

**Modified Rhyme Test .** If testing time is limited, or time is not available to thoroughly train subjects for the PB method, the second recommended choice is the Modified Rhyme Test (MRT) described by House et al. (1963). The test material consists of 300 words which are printed on an answer sheet in 50 groups of six words each. The talker reads one of the six words in the first group and each listener selects one word from the closed set of six alternatives. Unlike the PB test, little account is taken of word familiarity or of the relative frequency of occurrence of sounds in the language. This test has the advantage of requiring little or no training, and does not require a written response as is the case with PB tests. A chart for converting MRT scores to PB test scores is shown in figure 15-20.

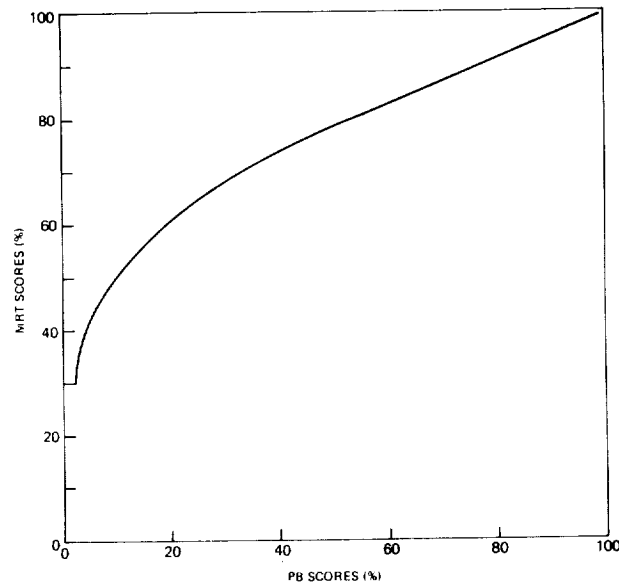


Figure 15-20. Relationship between MRT test scores and PB test scores.  
(Based on unpublished data from K. D. Kryter, 1964)

**Articulation Index Calculation.** Intelligibility of speech in noise may also be calculated from measures of the speech and noise levels through use of the Articulation Index (AI) (Kryter, 1962). AI can be calculated from octave-band measurements using the worksheets shown in figure 15-21 and table 15-7, provided the noise does not have any severe pure tone components and is steady in character without an extremely sloping spectrum. (Additional worksheets are available in the source document if the situation requires the use of 1/3-octave band measurements.)

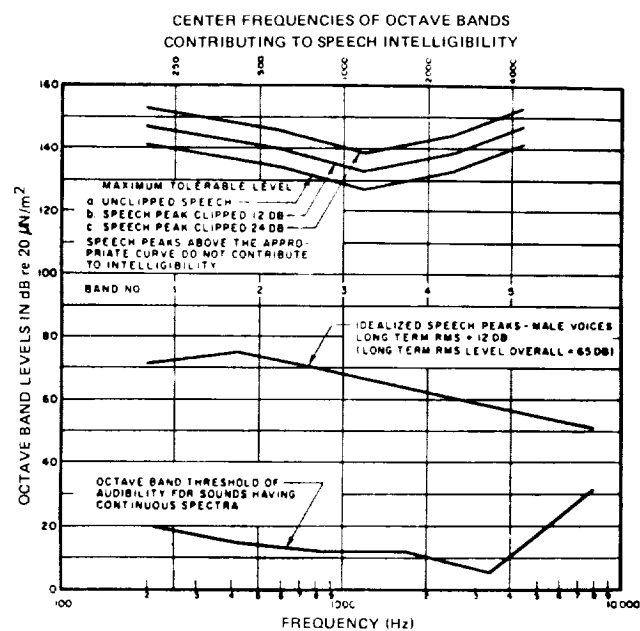


Figure 15-21. Worksheet for calculating Articulation Index by the octave band method using ANSI preferred frequencies. (Kryter, 1962)

Table 15-7

Worksheet for Calculating Articulation  
Index by the Octave Band Method  
(Preferred Octave Bands)

| Col 1           |           | Col 2                                    | Col 3      | Col 4         |
|-----------------|-----------|------------------------------------------|------------|---------------|
| Octave Band     | Frequency | Speech Peak-to-Noise<br>Difference in dB | Weight     | Col 2 X Col 3 |
| 1. 180 - 355 Hz | 250 Hz    | _____                                    | 0.0018     | _____         |
| 2. 355 - 710    | 500       | _____                                    | 0.0050     | _____         |
| 3. 710 - 1400   | 1000      | _____                                    | 0.0075     | _____         |
| 4. 1400 - 2800  | 2000      | _____                                    | 0.0107     | _____         |
| 5. 2800 - 5600  | 4000      | _____                                    | 0.0083     | _____         |
|                 |           |                                          | AI = _____ |               |

(Kryter, 1962)

The octave band method of calculating AI is as follows: (1) Plot the measured octave band SPL of the noise. (2) Adjust the idealized speech spectrum shown on the worksheet to reflect its actual level. (3) Measure the difference between the speech and noise in each band, and assign a value between zero and 30 dB. (4) Multiply this assigned value in each band by the appropriate weighting factor (this accounts for the difference in the importance among the several bands) and add the resultant numbers. This number, which is between zero and one, is the AI which may then be converted to PB intelligibility score through the use of figure 15-22.

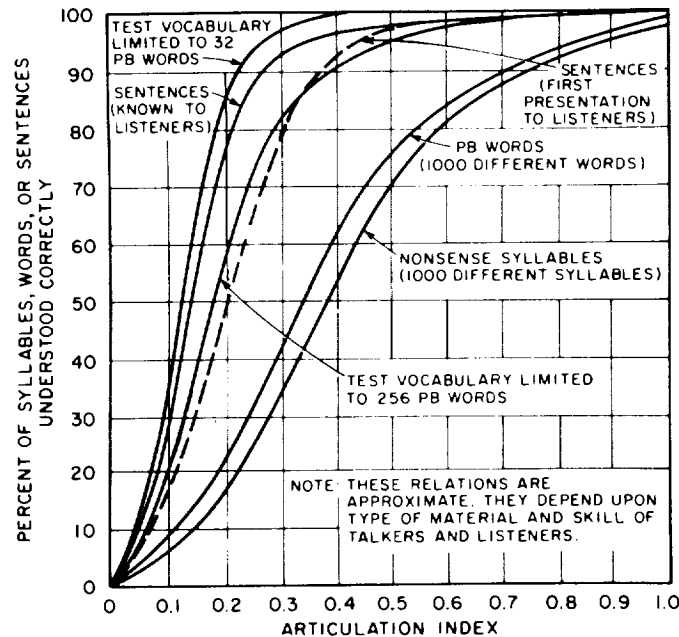


Figure 15-22. Relation between Articulation Index and various measures of speech intelligibility. (Kryter, 1970b)

The AI method of calculating speech intelligibility may be used for either direct or electrically-aided communication, provided only that the speech signal and noise levels at the ear are known.

#### **Annoyance: Community Response to Noise Exposure**

The term annoyance refers to the perceived noisiness, unwantedness, objectionableness, or unacceptableness of noise. Communities of noise-exposed residents may be annoyed and may respond collectively, or as individuals, in attempts to rid themselves of the intruding noises. Individual differences among group members make it very difficult to predict individual responses; however, group response prediction has achieved a high degree of sophistication and reliability.

Quantification and prediction of community response to noise exposure involves identification and/or measurement of many variables, including level, spectrum, duration, time of day, frequency of occurrence, type of residential neighborhood and amount of previous noise exposure. Integrating these data, with appropriate weighting, into a predictive scheme results in a single "composite" rating of the annoyance reaction to be expected. Such reactions range from no response, through occasional complaints by individuals, to concerted legal action by groups.

Two general approaches to the prediction of annoyance reactions enjoy wide acceptance. The first approach, typified by the Composite Noise Rating of Rosenblith and Stevens (1953), results in a qualitative prediction of community response without attaching to it a precise numerical value. Botsford (1969) has simplified this approach, as illustrated in figure 15-23, by reducing the measurement of level and spectrum to A- and C-weighted sound levels. This figure can thus be used to predict community responses to noise levels up to 95 dBA and 110 dBC.

The second approach involves computation of a numerical index of perceived noisiness which is then used to predict community response. Kryter's (1968) Effective Perceived Noise Level (EPNL) expressed in EPNdB, has found particular application in the evaluation of community response to aircraft noise [although, as Kryter (1970) indicates, the method is applicable to all types of community noise exposure]. The general relationship between EPNL and annoyance reactions is illustrated in figure 15-24.

It is not practical to recommend a single, optimum procedure for calculating EPNL since many new developments are rapidly taking place. The various existing procedures differ primarily in terms of the weighting to be assigned to the highest SPL during an occurrence of a noise, and the length of the integration time used in calculating perceived noise level. Sperry (1968) presents the calculation procedure used for Federal Aviation Agency certification of new commercial aircraft. Kryter (1968) reviews a variety of computation procedures, and (Kryter, 1970) describes his latest recommendations for EPNL calculation, including a discussion of its application to sonic boom problems. Department of Defense (1964) reports related procedures helpful in land use planning. Cole and von Gierke (1957) discuss community response to noise from missile static testing and launch operations.

## **Physiological (Nonauditory) Responses to Noise Exposure**

### **Low Level Stimulation**

It is now well established that noise exposure can affect human physiological processes and that measureable effects are obtained with noise exposure conditions involving little or no risk of TTS. The main concern of researchers is whether these effects of noise, which in some instances appear to be correlated with pathological effects and/or behavioral alterations, may represent a real hazard to the health and well-being of exposed persons.

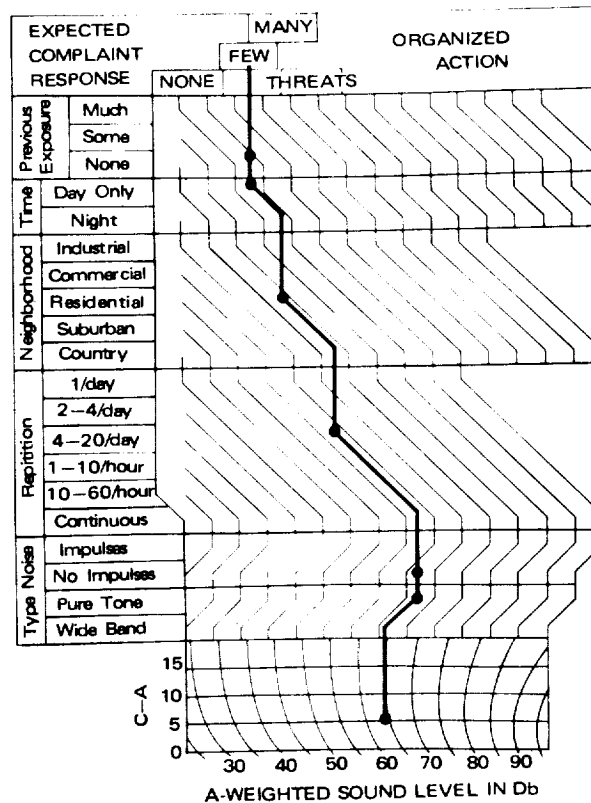


Figure 15-23. Annoyance of neighborhood sound levels. To use graph, locate in curved grid at bottom, point corresponding to sound levels of neighborhood noise under consideration and project directly above it into first of the 6 correction sections bounded by horizontal lines. Follow correction lane entered until reaching position opposite condition listed at left which applies to noise under consideration, and then proceed vertically, disregarding lanes, until next section is reached. Work upward through lanes of correction sections until reaching response to be expected at the top, e. g., if truck movements at a new loading station are to be cued by a whistle that will produce 65 dBA and 70 dBC at the nearest homes 10 to 15 times/day, then few complaints would be expected according to the line traced through the chart above. (Botsford, 1969)

Jansen (1969) dichotomizes physiological responses to noise into stress reactions and vegetative reactions. Stress reactions to unfamiliar stimuli, in general, show adaptation with repeated exposure as the stimuli become familiar and gain meaning to man, and hence are of less concern in the present context. It is the vegetative reactions to meaningless noise stimulation which is of primary concern here. Meaningless noise refers, for example, to the background noise found in industry, in the community and in the home. Adaptation to such noises has not been reported in many instances, and continued exposure may involve some risk of eventual interference with the health and well-being of workers.

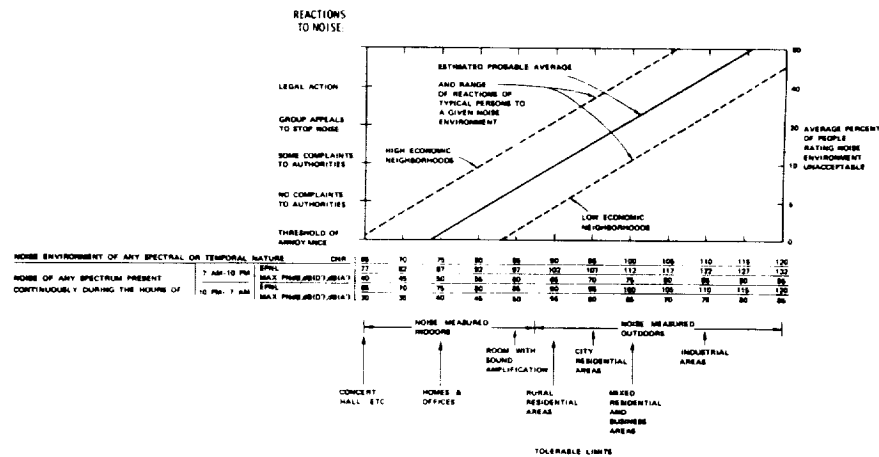


Figure 15-24. General reactions of people and communities to environmental noise. (Kryter, 1970)

Representative observations from studies cited by Anticaglia and Cohen (1969) and Jansen (1969) are summarized below:

- Noise exposure causes increases in the concentration of corticosteroids in the blood and brain and affects the size of the adrenal cortex. Continued exposure is also correlated with changes in the liver and kidneys and with the production of gastrointestinal ulcers.
- Electrolytic imbalances (magnesium, potassium, sodium and calcium) and changes in blood glucose level are associated with noise exposure.
- The possibility of effects on sex-hormone secretion and thyroid activity is indicated.
- Vasoconstriction, fluctuations in blood pressure, and cardiac muscle changes have been reported. Vasoconstriction in the extremities, with concomitant changes in blood pressure, have been found for noises of 70 dB SPL, and these effects become progressively worsened with higher levels of exposure.
- Abnormal heart rhythms have been associated with occupational noise exposure and this and other evidence supports the tentative conclusion that noise may cause cardiovascular disorders.
- Panian (1963) states that in Russia the cardiovascular symptoms outlined above are collectively referred to as "noise sickness."
- Yuganov et al. (1967) found that 10 to 30 days of exposure to noise levels of 75 dB produced electroencephalographic and cardiovascular alterations in astronauts similar to those described above. Reduction of the noise level to 65 dB resulted in no such observations at all for exposures of up to 60 days.
- With respect to *impulse*-noise exposure, Yuganov et al. (1966) reported that repeated exposure to simulated sonic booms having peak levels up to  $9 \text{ kg/m}^2$  ( $133 \text{ dB re } 20 \mu\text{N/m}^2$ ) caused alterations in electrocardiogram and

electroencephalogram traces as well as moderate bleeding in tympanic membrane epithelium, and they said that subjects reported headache, tinnitus and "fullness" in their ears.

### **Risk of Injury or Death from Steady Noise**

Studies of very intense steady acoustic stimulation have been carried out primarily with animals, and few data are available for human exposures. Three relevant observations follow:

- One instance of a ruptured human eardrum has been reported for exposure to 159 dB SPL at 6.5 kHz for 5 minutes (Davis et al, 1949).
- Mohr et al. (1965) reported no risk of bodily injury to astronauts from the intense, low-frequency noise simulating a space rocket launch, but a number of questions remain unanswered in this regard. Exposure to tones in the 1 to 100 Hz range should not exceed 2 minutes or 150 dB SPL, as these values appear to be close to the limits of human tolerance.
- Parrack (1966) calculated that for a 2 kHz whole-body exposure (probably not attainable in a practical situation) human lethality from overheating would require from 5 minutes at 167 dB SPL to 40 minutes at 161 dB. At 6 to 20 kHz the exposures required for lethality range from 5 minutes at 187 dB to 40 minutes at 181 dB SPL. Parrack's paper further indicates that ultrasonics pose no special hazard to man's life until the SPL exceeds 180 dB.

### **Blast and Impulse Noise Effects**

The effects of high-intensity blast waves on man are classed as primary, secondary and tertiary: primary effects are those resulting from the impact of blast waves on tissues; secondary effects are caused by flying debris set in motion by the blast; tertiary effects result from propulsion of the body. Only the primary effects of blast will be briefly summarized here.

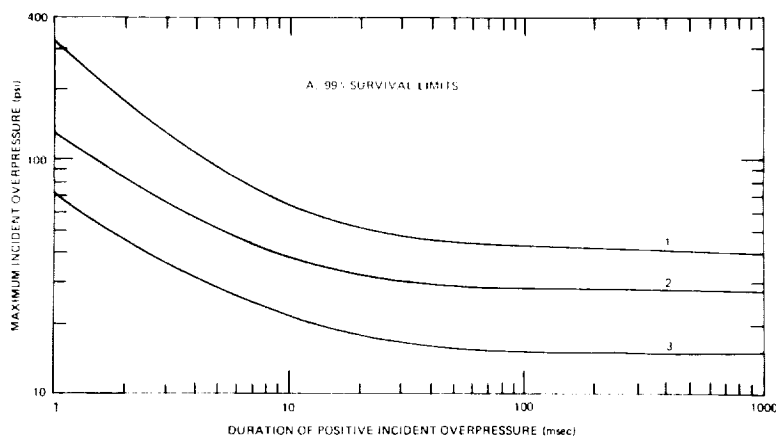
The following extrapolations of animal data to human exposures are valid only for exposure to single, fast-rising blast waves involving classical or near-classical waveforms:

- Risk of injury or death increases with increased pressure and/or duration, and with the presence of nearby reflecting surfaces.
- Risk of injury is lessened with increased rise time, and higher-than-normal ambient pressures.
- Gas-containing organs (ears, lungs, intestines) are very susceptible to blast injury.
- The eardrum is most susceptible: its threshold for rupture is about 5 psi.
- The lungs are most critical with regard to possible lethality: the threshold for lung damage (minor hemorrhage) is about 10 psi.

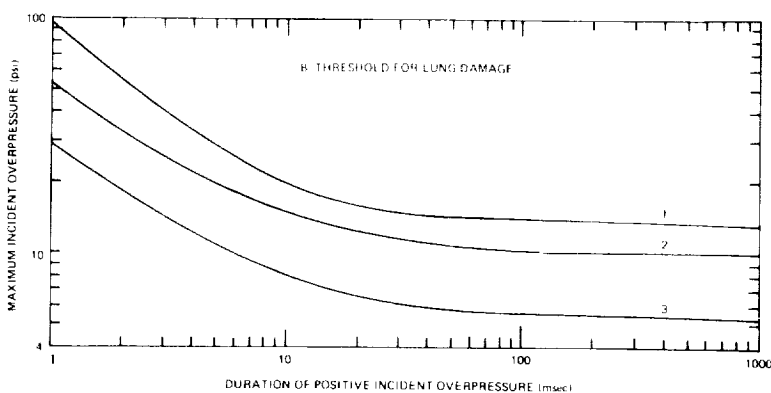


• Animals exposed to blast show evidence of central nervous system (concussive) damage--ataxia, paralysis, convulsions, dazed appearance, and lethargy--and often do not respond to noxious stimuli.

• Figure 15-25 shows 99 percent survival limits and lung damage thresholds as a function of peak overpressure and blast duration.



(a)



(b)

Figure 15-25. Blast exposure limits as a function of peak overpressure and duration. (A: 99% survival limits; B: threshold for lung damage; 1: long axis of body parallel to blast wave; 2: long axis of body perpendicular to blast wave; 3: thorax near a reflecting surface which is perpendicular to blast wave.) All curves relate to subjects facing any direction. (Bowen et al., 1968)

Few studies have been made of the effect of repeated, high-amplitude blast waves and impulse-noise waves. De Candole (1967) states that repeated blast exposure is responsible for the syndrome known as "battle fatigue." Anecdotal reports indicate that large caliber weapon instructors exposed to 50 impulses per day at about 10 psi complain of chest pains, nausea, and sleeplessness. Jacobson

et al. (1962) felt that it was necessary for subjects exposed to repeated impulses from a howitzer to wear a foam rubber "chest protector" at levels of 6 psi and higher. Tanenholtz (1968) recommends that artillery crewmen not be exposed to repeated blast at pressures above 7 psi, even when utilizing protection.

## Design Criteria

### Design Goals

It seems unlikely that noise and blast will ever be completely eliminated from man's environment. Therefore, steps must be taken to insure that the noise which reaches man's receptors is tolerable. The term "tolerable" may be interpreted in several ways. (1) It refers to the prevention of excessive hearing loss and unpleasant subjective sensations; criteria for this purpose are discussed below. (2) Prevention of injury from blast is also considered. (3) Further, tolerable noise exposure refers to limiting background noise levels to the extent required to minimize masking of speech communications, and (4) to providing noise levels in work areas that do not interfere with the performance of duties. (5) Also, community noise levels must be limited to prevent annoyance, complaints or threats of legal action.

Finally, one method of achieving tolerable noise levels at a person's ear is by the use of hearing protectors. Various protective devices and techniques are presented at the end of this section.

### Noise Exposure Limits

Documents developed to aid in specifying noise exposure limits are variously referred to as damage-risk criteria (DRC), damage risk contours, and hearing conservation criteria. The first two names point to a consideration which must not be ignored. "Damage risk" implies just that: there is always the risk of some TTS or PTS in a portion of the noise-exposed population. Because of the wide range of susceptibility to hearing loss (discussed earlier), it is neither philosophically realistic nor economically feasible to enforce DRC which will protect everyone (Cohen, 1963). Always, there is a risk that someone will lose a portion of his hearing sensitivity either temporarily or permanently. Thus, it is incumbent upon the user of any DRC to insure that he understands the risks involved.

It should be noted that the noise limits imposed by DRC refer to the noise which actually enters the ear canal. If the environmental noise exceeds the allowable limits, several means are available for reducing the levels to or below acceptable limits.

#### *Steady-State and Intermittent Noise DRC.*

CHABA DRC. The CHABA Damage Risk Criteria (DRC) (1965) was developed through the efforts of Working Group 46 of the NAS-NRC Committee on Hearing, Bioacoustics and Biomechanics. The acceptable limits

for end-of-day  $TTS_2$  are: 10 dB at or below 1 kHz, 15 dB at 2 kHz, and 20 dB at or above 3 kHz, in 50 percent of exposed ears. These TTS limits are considered to be equal to the maximum acceptable amounts of PTS after about 10 years of near-daily exposure. The allowance of less TTS in the lower frequencies is designed to provide additional protection for the speech-range frequencies, and the 10-15-20 dB TTS limits are related to the borderline criteria for compensable hearing loss. It is not safe to attempt to extrapolate the criteria to prevent PTS at intermediate number of years, nor the protection of different amounts of hearing. For such individualized applications, special criteria should be developed.

The CHABA steady noise DRC is presented in the form of 11 graphs relating the trade-offs among (1) spectrum, (2) exposure time up to 8 hours and, (3) SPL. Figure 15-26 shows the exposure limits for octave (and narrower) bands of noise, and figure 15-27 gives the limits for exposure to pure tones.

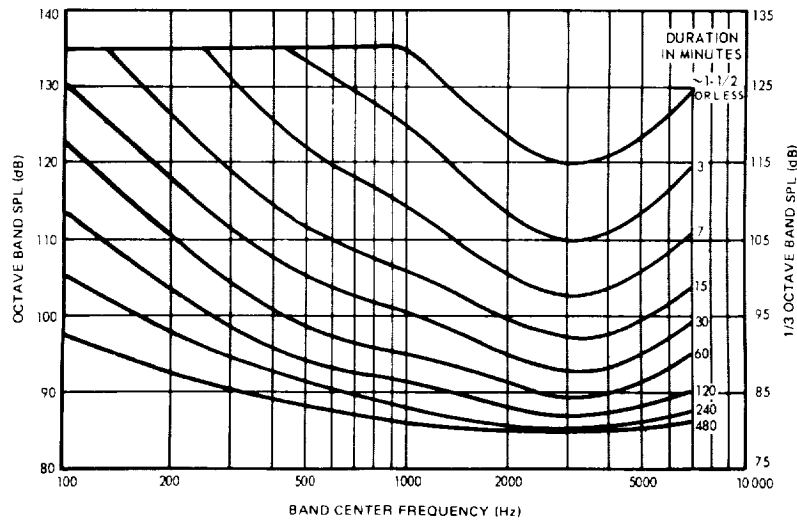


Figure 15-26. Damage risk contours for 1 exposure/day to octave (left-hand ordinate) and 1/3 octave or narrower (right-hand ordinate) bands of noise. Graph can be applied to individual band levels present in broad band noise. (CHABA, 1965)

The CHABA DRC's 8-hour exposure limit makes it inapplicable as a design criterion for extended space flight, but it is applicable to the protection of ground-service crews and other personnel who typically work 8-hour shifts each day. (See below for design criteria for extended space flight.)

Those regulations, which apply to noise, under the Occupational Safety and Health Act of 1970 include the limits on occupational noise

exposure. Noise exposure limits are stated in terms of A-weighted sound levels, and table 15-8 shows the permissible levels for exposures of 15 minutes to 8 hours per day. For octave band SPL data, a graph is provided for determining equivalent A-weighted sound levels, as shown in figure 15-28.

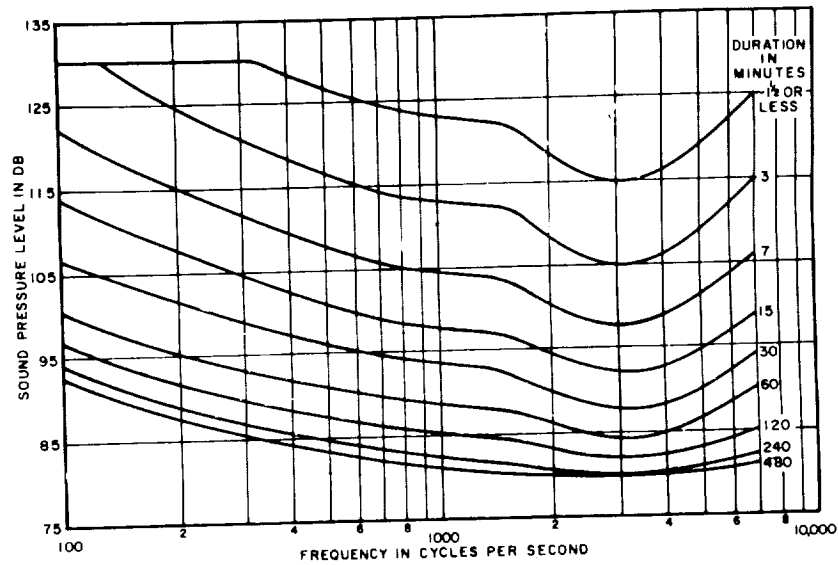


Figure 15-27. Damage risk contours for 1 exposure/day to pure tones. (CHABA, 1965)

Table 15-8

Occupational Safety and Health Act  
Permissible Daily Noise Exposure\*

| Duration (hr) | Sound Level (dBA) |
|---------------|-------------------|
| 8             | 90                |
| 6             | 92                |
| 4             | 95                |
| 3             | 97                |
| 2             | 100               |
| 1.5           | 102               |
| 1             | 105               |
| 0.5           | 110               |
| 0.25          | 115               |

\*When the exposure is intermittent at different levels the fraction  $C_1/T_1 + C_2/T_2 + \dots + C_n/T_n$  should not exceed unity to meet the exposure limit.

$C_n$  = total exposure time at the specified noise level.

$T_n$  = total exposure time permitted at the specified level.

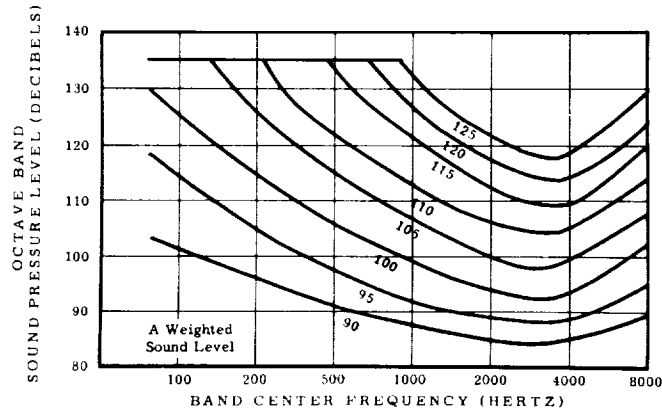


Figure 15-28. Contours for determining equivalent A-weighted sound level. Graph is used in interpreting octave-band sound levels according to the provisions of Occupational Safety and Health Act. (OSHA, 1970)

**Noise Limits for Extended Space Flight.** To obviate the possibility of TTS during extended space flights (up to 60 days) the background noise level inside spacecraft should not exceed 65 dB overall (Yuganov et al., 1967).

**Ultrasonic Noise Limits.** To prevent TTS and unpleasant subjective responses to ultrasonic noise, the SPL must not exceed 75 dB in 1/3-octave bands centered at 8 to 16 kHz or 110 dB at 20 to 31.5 kHz (Action, 1968).

**Low-Frequency and Infrasonic Noise Limits.** To prevent physiological injury from low-frequency and infrasonic noise (1 to 100 Hz) the limits shown in table 15-9 must not be exceeded. Even at these limits, experienced astronauts may report transient unpleasant sensations. Above these levels wearing of hearing protective devices is *mandatory*.

Table 15-9

Low-Frequency and Infrasonic Noise Exposure Limits

| Frequency*<br>(Hz) | SPL<br>(dB) | Duration**<br>(min/day) | Notes                                              |
|--------------------|-------------|-------------------------|----------------------------------------------------|
| 1 - 7              | 150         | 4                       | Use of ear plugs will reduce unpleasant sensations |
| 8 - 11             | 145         | 4                       |                                                    |
| 12 - 20            | 140         | 4                       |                                                    |
| 21 - 100           | 135         | 20                      | Without protection                                 |
| 21 - 100           | 150         | 20                      | With ear plugs                                     |

\*Refers to pure tones or to octave bands with center frequencies as indicated.

\*\*Refers to one exposure per day with at least 24 hr elapsing between successive exposures. (Wilhold et al., 1970)

**Impulse-Noise Limits.** The most comprehensive DRC for impulse noise exposure is that published by CHABA (1968) and based on the formulations of Coles et al. (1967, 1968). This DRC assumes the same TTS limits as does the CHABA (1965) steady noise DRC. However, the impulse noise DRC is designed to protect 95 percent of ears exposed. The basic DRC (figure 15-29) assumes a daily exposure of 100 impulses distributed over a period of from 4 minutes to several hours and that the impulses reach the ear at normal incidence.

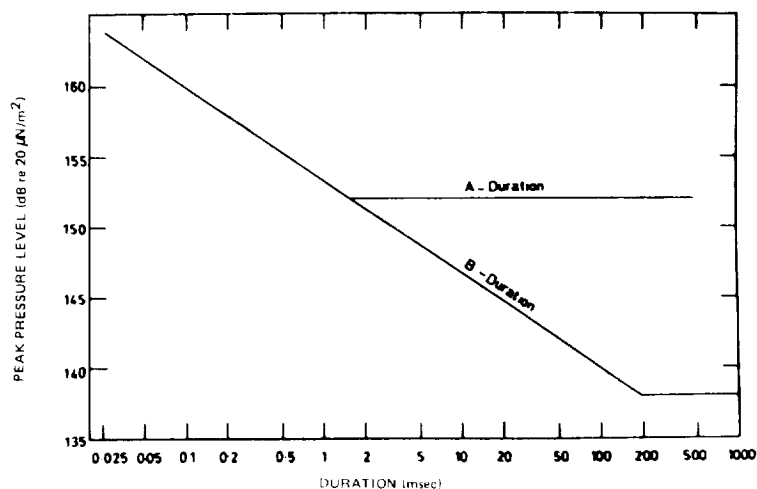


Figure 15-29. Basic limits for impulse noise exposure assuming 100 impulses/day and other conditions as stated in text. (CHABA, 1968)

Two correction factors are included in the DRC. First, if the pulses reach the ear at grazing incidence (rather than normal) the curves can be shifted upward by 5 dB. Second, if the number of impulses in a daily exposure is some value other than 100 (i.e., 1 to 1000) an adjustment can be made according to the curve shown in figure 15-30.

### Blast Exposure Limits

To minimize temporary or permanent hearing loss from blast, the impulse noise criteria stated above should be used. To avoid other physiological injury from fast rising, long duration blast waves, the following pressures must not be exceeded:

5 psi (unprotected) to prevent eardrum rupture

10 psi (ears protected) to prevent lung damage. (See figure 15-25)

### Speech Interference Criteria

In a preceding section, calculation of the Articulation Index was discussed. AI, as a method of estimating the masking effect of noise on speech

intelligibility, is quite involved. A relatively simple method was devised by Beranek (1947) and later modified by Webster (1969). Webster's method, called the three-band preferred octave speech-interference level (PSIL), is obtained by averaging the noise levels in the 500, 1000, and 2000 Hz octave bands.

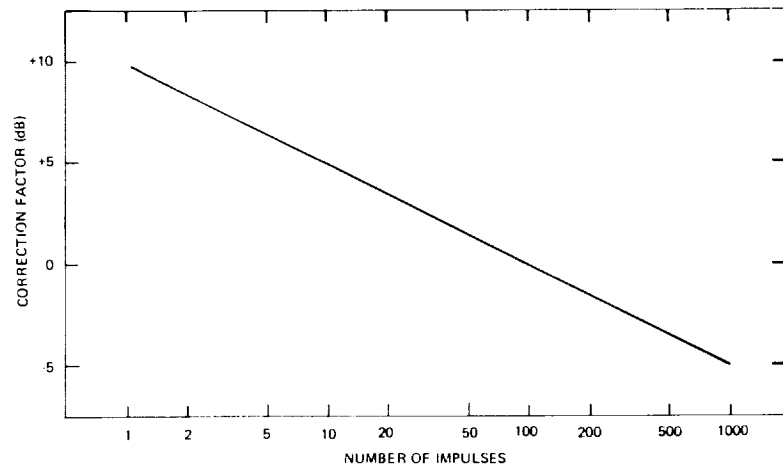


Figure 15-30. Correction factors to be added to ordinate of figure 15-29 to allow for daily impulse noise exposures different from 100 impulses. (CHABA, 1968)

Once the PSIL value has been calculated, reference to figure 15-31 may be made to determine what voice level is required to provide acceptable intelligibility at a given talker-to-listener distance. "Acceptable intelligibility" here corresponds to a PB intelligibility score of 75 percent and assumes that no lipreading occurs. The "expected voice level" results from the fact that a speaker tends to raise his voice level about 3 dB for each 10 dB increase in ambient noise starting at about 50 dB PSIL when he receives no feedback from the listener. The "communicating voice" is that effort produced when a talker receives instantaneous feedback of success or failure from the listener.

### Workspace Noise Criteria

Beranek (1960) presents criteria for limiting workspace background noise where communications interference, loudness, or annoyance of noises are an important design consideration. These noise criterion curves, or "NC" curves, are widely used as workspace design criteria. Figure 15-32 shows the allowable octave-band SPL (for both commercial and preferred octave bands) and table 15-10 identifies typical work spaces with the appropriate NC curves. These curves were derived in such a way that each octave band contributes about equally to the loudness of the background noise. To be acceptable, the noise level in each octave band must not exceed the level permitted by the selected NC curve. It should be noted that when using commercial frequencies the NC number is also the SIL for that particular spectrum.

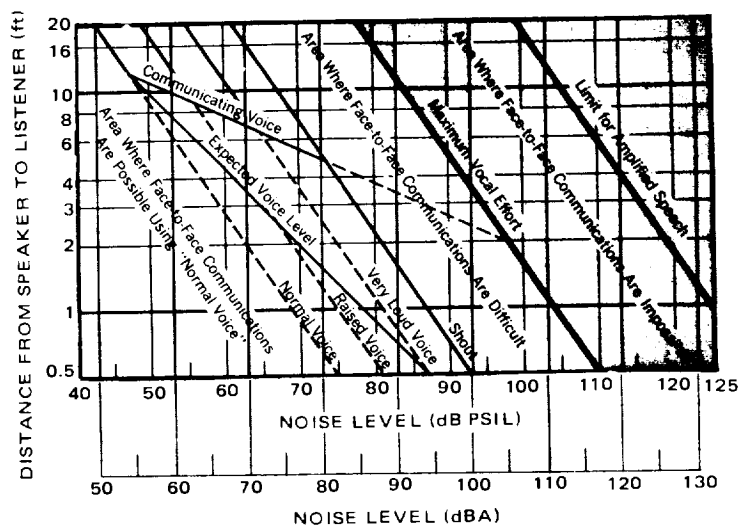


Figure 15-31. Voice level and distance between talker and listener for satisfactory face-to-face speech communications, as limited by ambient noise level. Along abscissa are two generally equivalent objective measures of noise level: average octave-band level in octaves centered at 500, 1000, and 2000 Hz, called the three-band preferred octave speech-interference level (PSIL), and A-weighted sound level meter reading (dBA). Example: Jet aircraft cabin noise is roughly  $80 \pm 2$  dBA. At 80 dBA with raised voices, seatmates can converse at 2 ft, and, by moving a little, can lower their voices to normal level and converse at 1 ft. To ask the stewardess for an extra cup of coffee from the window seat (4 ft), one would need to use his communicating (very loud) voice. (Webster, 1969)

The recommended NC level inside a spacecraft without engines operating is NC-55.

### Community Noise Criteria

It should be clearly recognized that the final decision as to criteria for community noise exposure is an administrative one. Scientific and technical data may aid in answering questions, but it remains the province of society and legal administrative officials to make ultimate decisions (Galloway & von Gierke, 1966). Only society, and its official representatives, can decide what price it is willing to pay for community noise control.

FAA (1969) lists EPNL limits for new commercial aircraft. Department of Defense (1964) recommends PNL limits for land use planning around airports. Fredrikson (1970) discusses zoning ordinances for limiting community noise.

### Hearing Protection

Four general approaches may be taken to prevent sound from reaching the ear: (1) The person may be removed to a distance from the noise source such that spherical divergence and excess attenuation reduce the noise level to an



acceptable extent. (2) A physical barrier may be placed between the noise or blast source and the man. (3) The natural "aural reflex" action of man's middle-ear muscles may be stimulated as a means of protection. (4) A mechanical hearing protector may be placed over, or in, the ear canal to attenuate sound energy. Discussion of this latter approach to noise reduction will occupy the bulk of this section.

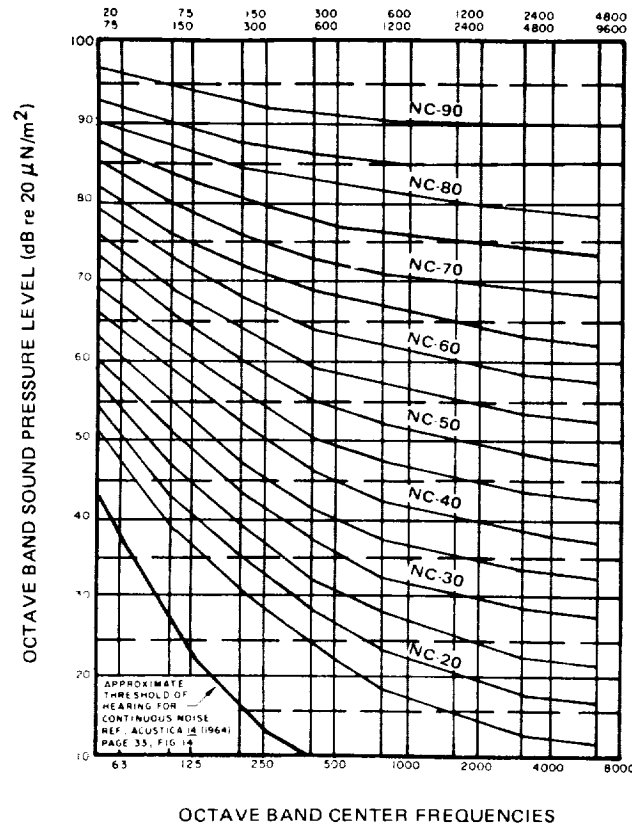


Figure 15-32. Noise criteria (NC curves) referred to preferred octave bands (lower abscissa) and commercial octave bands (upper abscissa). (From Schultz, 1968) NC 75-90 curves are present authors' own extrapolations which have been found to be very useful in practical applications. NC-55 is design criterion for Apollo spacecraft during nonpowered flight.

**Mechanical Hearing Protection.** Situations often arise in which it is neither economical nor practical to remove people to a distance from a noise source or to place a barrier between them and the source. In such cases the use of mechanical hearing protection is recommended to reduce the noise to a level which is not hazardous to hearing and/or will permit effective communication.

Table 15-10  
Recommended NC Curves for Various Work Spaces

| NC Curve | Type of Work Space                                                                                                     | Communication Equivalent                                                                                                      | Office Application                                                                     |
|----------|------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| 90       |                                                                                                                        | Noise-attenuating headset required                                                                                            | Not recommended                                                                        |
| 80       |                                                                                                                        | Communication very difficulty; telephone use unsatisfactory                                                                   | Not recommended                                                                        |
| 70 - 80  |                                                                                                                        | Raised voice range 1-2 ft; shouting range 3-6 ft; telephone use very difficult                                                | Not recommended                                                                        |
| 60 - 70  |                                                                                                                        | Raised voice range 1-2 ft; telephone use difficult                                                                            | Not recommended                                                                        |
| 55 - 60  |                                                                                                                        | Very noisy; not suited for office; telephone use difficult                                                                    | Not recommended                                                                        |
| 55       | Spacecraft during nonpowered flight                                                                                    |                                                                                                                               |                                                                                        |
| 50 - 55  |                                                                                                                        | Unsatisfactory for conferences of over 3 people; telephone use slightly difficult; normal voice at 2 ft; raised voice at 3 ft | Areas with typists and accounting machines                                             |
| 40 - 50  | Restaurants, sports coliseums                                                                                          | Conferences at 4-5 ft table; telephone use slightly difficult; normal voice at 3-6 ft; raised voice at 6-12 ft                | Large drafting rooms                                                                   |
| 35 - 40  |                                                                                                                        | Conferences at 6-8 ft table; telephone use satisfactory; normal voice at 6-12 ft                                              | Medium sized offices                                                                   |
| 30 - 35  | Libraries, hospitals, motion picture theatres, home sleeping areas, assembly halls                                     | Quiet office; conferences at 15 ft table; normal voice at 10-30 ft                                                            | Private or semi-private offices; reception rooms; conference rooms for up to 20 people |
| 25 - 30  | Courtrooms, churches, home sleeping areas, assembly halls, hotels and apartments, TV studios, music rooms, schoolrooms | Very quiet offices; large conferences                                                                                         | Executive offices; conference rooms for 50 people                                      |
| 20 - 25  | Legitimate theatre, concert halls, broadcasting studios                                                                |                                                                                                                               |                                                                                        |

(Modified from Beranek 1960)

Hearing protectors will often improve person-to-person and loudspeaker-to-person communication in noise (Acton, 1967). The same speech signal-to-noise ratio reaches the ear with and without protection in such cases, but the use of protection may cause the speech signal to reach the ear at a level in the optimum range for speech intelligibility (i.e., overall RMS level of about 70 dB). This effect may, therefore, influence the selection of hearing protection for use in a given situation. It would be undesirable to recommend a highly effective hearing protector for use in a relatively low noise level, for example, since this might reduce the speech signal to below the optimum speech level.

Mechanical hearing protectors fall into four general categories: earplugs, semi-inserts, earmuffs, and helmets.

Earplugs are available in two forms: (1) preformed rubber or plastic plugs supplied in up to seven sizes, and (2) disposable plugs, such as wax-impregnated cotton, or "glass down" (a very fine, nonirritating glass wool).

Dry cotton is not recommended for use since it provides negligible sound attenuation (2 to 5 dB in the lower frequencies; 6 to 10 dB at the higher frequencies) and may provide a false sense of security.

In order to be maximally effective, earplugs must be properly fitted for size. It is not unusual to find people who require a different size plug for each ear. Furthermore, the plugs must be properly inserted each time they are used: they must be tight to be effective. Finally, the plugs must be kept clean to minimize the possibility of ear infections.

Semi-inserts are available in one size only and are pressed against the entrance to the ear canal by a light, spring-loaded headband. If frequent donning and doffing are required they are very convenient and, unlike bulky earmuffs, may easily be hung around the neck when not in use. On the other hand, semi-inserts may not provide as effective a seal against sound as either earplugs or earmuffs.

Earmuffs are made in one size only and almost everyone can be fitted satisfactorily with little difficulty. They attenuate sound as well as, or better than, earplugs at high frequencies, but are slightly poorer than plugs below 1 kHz. The primary disadvantages of earmuffs are their bulk and relative expense. They do not, however, entail the fitting and insertion problems of earplugs. Another advantage, in certain situations, is that a supervisor can readily determine from a distance that all of his personnel are wearing their hearing protectors. Where very intense noise levels exist, it may be desirable to wear *both* earplugs and earmuffs. The total sound attenuation does not, of course, equal the sum of the individual protector attenuations, but this combination will ordinarily provide increased attenuation at most frequencies, with particular benefit being derived at the low frequencies (Webster & Rubin, 1962).

Helmets can provide more attenuation than the aforementioned devices if they cover the greater portion of the head. The acoustical importance of a helmet increases when the SPL reaches a point where bone-conducted sound

transmission through the skull becomes a controlling factor. In cases other than this the use of helmets for hearing-protective purposes alone is not justified. The maximum attenuation which can be provided by a plug, muff or semi-insert is about 35 dB at 250 Hz and is greater at higher frequencies (Zwislocki, 1955). After reductions of this magnitude, the remaining sound is conducted through the bones of the skull directly to the inner ear (Rice & Coles, 1966). An astronaut's helmet, which seals off the whole head, can provide an additional 10 dB of protection. Beyond this point, conduction of sound by the body is the limiting factor.

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| 13. ABSTRACT<br><br><p>The effects of noise and blast upon man are complex and varied. Although this report is directed primarily toward the noise produced during space activities the effects upon man will be similar regardless of the specific noise source.</p> <p>Data are presented dealing with physical acoustics, the characteristics of sound and appropriate noise measurement techniques. Hearing loss resulting from both steady-state and impulse noise is discussed along with the factors influencing its acquisition and recovery and the resultant effects upon performance. Subjective and behavioral response to noise is discussed in terms of masking of auditory signals and speech, annoyance and general observation. Current research in the area of nonauditory effects is reviewed varying from cardiovascular alterations to the risk of death.</p> <p>Current design criteria are presented for both steady-state and impulse noise for both workspaces and communities.</p> |                                                                             |                                                    |

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