VI. DEVELOPMENT OF THE STANDARD

Attempts at limiting human exposure to noise have been based on damage risk criteria. The purpose of such criteria is to define maximum permissible levels of noise for stated durations which, if not exceeded, would result in an acceptably small effect on hearing levels over a working lifetime of exposure.

Previous Damage Risk Criteria

a. Damage Risk Criteria Before 1950

Early efforts at determining the maximum safe level of exposure relied heavily on over-all levels of sound pressure. A listing of criteria developed prior to 1950 is presented in Table VIII. As may be seen from the table, there was, even at that time, quite a diversity of opinion with regard to the limit of safe exposure to noise. Estimates ranged from a low of 75 dB SPL[67] to a high of 100 dB SPL.[68-71] This situation was further complicated in 1945 by Goldner's suggestion that a nominal daily exposure for at least two years to a noise having an overall sound pressure level of 80 dB could be hazardous to hearing.[72]

In tracing the possible sources of error in these pre-1950 criteria, Kryter[73] suggested that one problem inherent in most of the studies was the high ambient noise levels-which characterized the hearing testing-environments. It was thought that such high ambient noise levels could account for an over-estimation of the degree of hearing loss by as much as 10 to 15 dB. Probably the greatest source of error, however, was the fact that exposures were characterized using overall sound pressure level and no other factors.

b. Damage Risk Criteria Since 1950

It was apparent by 1950 that proposed limits must consider, in addition to intensity, other physical dimensions and characteristics of noise exposure. In 1953, Rosenblith and Stevens[74] published an extensive document entitled "Noise and Man" in which they delineated the following variables important to the development of damage risk criteria:

1. Measurement of spectral distribution (Noise Spectrum).

2. Determination of the temporal characteristics of exposure (Noise Duration).

3. Identification of a protection goal (Biologic Response).

In the discussion which follows, selected damage risk criteria listed in Table IX, will be compared and contrasted with respect to the above variables. The table represents a compilation of most criteria developed between 1950 and 1971, and where appropriate, criteria expressed in octave band levels have been converted to equivalent dBA. For purposes of performing these conversions a "pink" noise spectrum (i.e., equal sound pressure level in each octave band), typical of many common industrial noises, was assumed.

c. Criteria Based on Octave Band Levels

Beginning with Kryter[73] in 1950, concern shifted from measurement of noise based solely on overall sound pressure to measurements which are more indicative of the response of the hearing mechanism. Consistent with this thinking, several modern damage risk criteria have emphasized limit setting by frequency bands, usually one octave in width. Two lines of evidence were responsible for this shift in thought. First of all, data on minimum audible field sensitivity[75] and measurements of equal loudness[76] indicated that the ear was not equally sensitive at all frequencies. It was found that the ear is most sensitive to acoustic stimuli in the frequency range 2000 - 4000 Hz, and less sensitive to frequencies both below and above this range. Shown in Figure 8 are several damage risk criteria (DRC) developed between 1952 and 1966. For comparison, the 40 phon equal loudness curve[76] is presented in the lower part of this figure As may be seen from this figure, although the DRC differ in estimates of safe sound pressure level per octave, they all weight the spectrum similarly.

The second major impetus for measurement of noise based on octave band analysis came from research which indicated that, at least for most audiometric frequencies, the amount of threshold shift observed (either temporary or permanent) was closely related to the frequency or spectrum of the stimulus. Results of "stimulation deafness" (temporary threshold shift) studies indicated that for pure tone stimuli the maximum shift in hearing appears to be about one-half octave above the frequency of total stimulation.[77-79] Similar findings were reported for octave bands of noise and broadband noise by Davis et al.,[77] Kylin,[29] and Ward.[30] However, for these latter stimuli there was some difference of opinion as to the exact location of maximum effect. Davis et al.[77] and Kylin[29] suggested that the maximum effect occurs one-half octave to one octave above the center frequency of the octave band, whereas, more recently Ward[30] found that the maximum change in hearing occurs one-half octave to one octave above the upper cut-off frequency of the noise.

Prior to 1956 damage risk criteria set as a goal for protection (see Protection Goal), the prevention of hearing loss at all frequencies. This necessitated assessment of the noise at each octave band. After this time, however, much more qualified protection goals were established (usually protection of loss in the so-called "speech frequencies") such that only knowledge of the sound pressure in certain critical octave bands (not to be confused with aural critical bands) was required in order to assess the risk of noise exposure to hearing. This approach characterized the damage risk criteria developed by the Air Force in 1956, The American Academy of Ophthalmology and Otolaryngology in 1957, the International Standards Organization in 1961, and the American Academy of Ophthalmology and Otolaryngology in its revision of the 1957 criteria in 1964 (see Table IX).

The procedure for rating noise hazards by this mehtod consists of measuring the octave band levels in the critical octaves, and then comparing the measured levels with damage risk contours. This is best exemplified by the use of the "Noise Rating" curves developed by the International Standards Organization.[80] The octave band levels of the noise are measured and then compared with the noise rating curve (Figure 9). The highest curve which is exceeded by the level of these bands yields the noise rating number (N). For this particular scheme, a noise rating of 85 was suggested as the protection criterion.

<u>The Use of A-weighted Sound Level</u>

Since the publishing of the first Intersociety "Guidelines for Noise Exposure Control,"[81] a relatively new approach, A-weighted sound level measurement, has become a popular measure for assessing overall noise hazard. As stated in Part III, the weighting on the A-scale approximates the 40-phon equal loudness contour (Figure 8). Use of the A-weighting is thought, therefore, to insure the rating of noises in a reasonably similar manner as would the human ear.

Several studies have been conducted in order to evaluate the efficacy of using A-weighted sound levels in rating hazardous exposures to noise. In a study of 580 industrial noises, Botsford[82] showed that the A-weighted sound level indicated the hazard to hearing as accurately as did limits expressed as octave band sound pressure levels in 80% of the cases and was slightly more conservative than octave band measures in 16% of the noises. Passchier-Vermeer[26] found that, except in one noise condition, sound level in dBA was as accurate as Nose Rating (NR) in estimating noise induced hearing loss. In a study of hearing loss in 759 subjects, Robinson[83] concluded that the error incurred from using dBA in predicting hearing level was within ± 2 dB, even for noises ranging in slope from + 4 dB/octave to -5 dB/octave. A recent study[84] found that even though dBA perhaps discounted too much low frequency energy, in all cases but one it predicted TTS_2 resulting from exposures to noises of different spectra (slopes of -6 dB/octave, 0 dB/octave, and 6 dB/octave) as well as or better than other noise rating schemes which employed spectral measurements in octave-bands.

As a result of its simplicity and accuracy in rating hazard to hearing, the A-weighted sound level was adopted as the measure for assessing noise exposure by the American Conference of Governmental Industrial Hygienists (ACGIH)[85] and by an Intersociety Committee[27] consisting of representatives from the American Academy of Occupational Medicine, American Academy of Opthalmology and Otolaryngology, ACGIH, Industrial Hygiene Association, and the Industrial Medical Association. A-weighted sound level measurement was also adopted by the U.S. Department of Labor as part of the Occupational Safety and Health Standards[86] and by the British Occupational Hygiene Society in its Hygiene Standard for Wide-Band Noise.[87]

In keeping with the several precedents which have been established for its use in rating the hazard resulting from industrial noise exposure, and because it has been shown to be a reasonably accurate measure of such hazard, the A-weighted sound level measurement has been recommended for use in rating noise hazard in the Recommended Standard.

Protection Goal

The limit of noise exposure that is established ultimately depends upon the degree of hearing which is to be protected and the number of persons in an exposed population to be protected. If a very strict protection criterion is contemplated such that no person exposed to noise will develop hearing loss at any frequency, the maximum permissible noise level governing a daily, or near daily, exposure would be quite low. Conversely, if the protection goal were to permit a certain amount of hearing loss in a small percentage of workers over a working lifetime, then the permissible exposure level would be raised accordingly. For example, Figure 10 compares the permissible levels of exposure for an eight-hour day recommended by the National Academy of Sciences, National Research Council Committee on Hearing, Bioacoustics and Biomechanics (NAS-NRC) CHABA Working Group 46 with the damage risk criterion recently proposed by Kryter[88] for the same amount of exposure. Although both criteria are based upon either the same or similar types of data, the damage risk level is much higher in the CHABA criterion than in that proposed by Kryter. The major reason for this difference is that CHABA established as its protection goal attainment and no more than 10 dB of permanent threshold shift at 1000 Hz, 15 dB at 2000 Hz, and 20 dB at 3000 Hz in 50% of the people exposed to noise; whereas, Kryter set as his protection goal attainment of "0" dB of threshold shift at the frequencies

2000 Hz and below, and 10 dB of shift in the frequencies above 2000 Hz in 75% of the people exposed to noise.

The problem is further illustrated by a comparison of the protection criteria developed by the Intersociety in the Guidelines for Noise Exposure Control with the Hygiene Standard for Wide Band Noise[87] developed by the British Occupational Hygiene Society. Both standards established 90 dBA as the limit for a near daily 8-hour-per-day continuous exposure. However, as the following quotations indicate, there is quite a difference of opinion as to how much protection is actually afforded by 90 dBA:

1. "In the poplulation exposed to 90 dBA to age 50 - 59, the amount of impairment is increased 10 percentage points (ten more persons per 100 exposed) as compared to the population with no occupational exposure." (Intersociety, 1970)

2. "A noise emission of 105 dB (equivalent to 90 dBA for a working lifetime) is acceptable exposure on the basis that no more than 1 percent of exposed persons will experience handicap due to noise after lifetime exposure." (British Occupational Hygiene Society, 1971)

The difference here, as in the previous example, follows from a difference in the definition of the protection goal, specifically, the definition of hearing impairment or hearing handicap. The first critieria (Intersociety, 1970) adopted the AAOO-AMA definition of hearing impairment.[15] This definition states that hearing impairment begins as the average hearing level at 500, 1000, and 2000 Hz exceeds 15 dB re ASA S3.6 1951 (25 dB re ANSI S3.6-1969). Conversely, The British Occupational Hygiene Standard defined as its "low fence" of impairment an average permanent noise induced threshold shift (not to be confused with hearing level) of 40 dB in the six frequency range 0.5 - 6.0 KHz for 30 years of exposure. Recently, Robinson[89] computed hearing impairment risk values on the British data using the AAOO-AMA definition of hearing impairment. His figures indicate that near daily 8-hour exposure to continuous noise at a level of 90 dBA for 40 years would result in an increase in hearing impairment in between 13 to 15 persons per 100, depending upon the incidence figure of the non-noise exposed control population used for comparison. This "risk" value is comparable to the one presented by the Intersociety Committee[27] but about 6 - 8% below the International Standards Organization value for the same exposure.[90]

The question of how much hearing should be protected and in what percentage of the people hearing losses of certain magnitudes should be permitted has long been an issue of much controversy. The ultimate decision, according to Eldredge,[91] must be based on social and humane values.

Historically, the most common protection goal has been one directed at the preservation of hearing for speech. Direct measures for evaluating hearing for speech have been, and are being, developed. These tests generally fall into two classes: those which measure the threshold of speech or the ability to hear speech and those which measure discrimination, or the ability to understand speech. Although speech tests have been widely accepted for use in aural diagnostics, several objections have been raised as to their use and validity in industrial testing. These are: (1) Speech test items are sometimes unfamiliar to the listener; (2) Speech tests frequently measure the size of one's vocabulary as well as hearing impairment for speech; (3) Several speech tests or different forms of a single test designed to measure the same speech hearing function may yield different results; and

(4) Considerable training is required on the part of the examiner to administer and score speech tests. It has become, therefore, a common practice to measure pure tone sensitivity and relate hearing levels at certain specific frequencies to the ability to hear and understand speech.

In 1929, Fletcher[92] proposed what has now become known as his "Point 8" formula whereby the ability to hear everyday speech was estimated by multiplying the hearing levels at 500, 1000, and 2000 Hz by 0.8 and then computing the average over these three frequencies. The major contribution of this formula was the introduction of the concept that hearing loss for speech could be estimated by the average hearing levels at what has now become known as the "speech frequencies"-500, 1000, and 2000 Hz.

The American Medical Association[93] in 1947 recommended that hearing loss for speech be determined by the pure tone hearing losses at 500, 1000, 2000, and 4000 Hz. The four frequencies were given a weighting in accordance with what was presumed to be the importance of each frequency in hearing for speech (i.e., 15% at 500 Hz, 30% at 1000 Hz, 40% at 2000 Hz, and 15% at 4000 Hz). This guideline further suggested that hearing loss for speech does not begin until the weighted average hearing loss equaled 10 dB, and total loss for speech hearing occurred when the loss at 500 Hz reached 90 dB or the losses at the other 3 frequencies reached 95 dB.

In a later article which reviewed the assumptions in computing hearing loss for speech, the AMA[94] made the following observations and recommendations:

(1) The 1947 formula was inadequate for calculating hearing loss for speech in sensorineural hearing loss. (This is particularly interesting in that the method used today for computing hearing loss for speech, developed by the AAOO in 1959 and accepted by the AMA in 1961, eliminated the most

sensitive indicator of sensorineural hearing loss (i.e., losses at 4000 Hz.))

(2) Everyday communication should be the basis for evaluation of hearing disability.

(3) Losses greater than 15 dB (re ASA, 1951 Zero Audiometric standard) at 500, 1000, and 2000 Hz are abnormal and usually noticeable by the individual in everyday communications. Furthermore, a loss greater than 30 dB at 4000 Hz can be considered abnormal.

A new formula was developed by the Subcommittee on Noise of the American Academy of Ophthalmology and Otolaryngology (AAOO). This formula was subsequently adopted by the AAOO Committee on Conservation of Hearing[95] in 1959 and by the American Medical Association[15] in 1961. The bases of this formula are explained by the following excerpts taken from the "Guides to the Evaluation of Hearing Impairment" published in the Journal of the American Medical Association.[15]

> "Estimated hearing level for speech is the simple average of hearing levels at the 3 frequencies of 500, 1000, and 2000 cycles per second (cps).
>
> "Ideally, hearing impairment should be evaluated in terms of ability to hear everyday speech under everyday conditions. The ability to hear sentences and to repeat them correctly in a quiet environment is taken as satisfactory evidence for correct hearing of everyday speech. Because of present limitation of speech audiometry, the hearing loss for speech is estimated from measurements made with a pure tone audiometer. For this estimate, the simple average of the hearing levels at the 3 frequencies 500, 1000, and 2000 cps is recommended.

"In order to evaluate the hearing impairment, it must be recognized that the range of impairment is not nearly so wide as the audiometric range of human hearing. Audiometric zero, which is presumably the average normal threshold level is not the point at which impairment begins. If the average hearing level at 500, 1000, and 2000 cps is 15 dB or less, usually no impairment exists in the ability to hear everyday speech under everyday conditions."

The only major change in this formula from 1959 to the present time has been the result of the change in audiometric reference for hearing level (HL). The 15 dB average hearing level at 500, 1000, and 2000 Hz referenced to the 1951 ASA standard[96] corresponds to a 25 dB average hearing level at the same frequencies according to the recent reference pressure adopted by the American National Standards Institute.[97]

On the basis of the results of recent research which has investigated the relationship between pure tone hearing loss and hearing loss for speech, a slightly different definition of "hearing impairment" has been adopted for the purposes of this document. Simply stated, hearing impairment for speech communication begins when the average hearing level at 1000, 2000, and 3000 Hz exceeds 25 dB re ANSI (1969). The principle reasons for this definition are as follows:

1. The basis of hearing impairment should be not only the ability to hear speech, but also the ability to understand speech.

2. The ability to hear sentences and repeat them correctly in quiet is <u>not</u> satisfactory evidence of adequate hearing for speech communication under everyday conditions.

3. From (1) and (2) above, the ability to understand speech under everyday conditions is best predicted on the basis of the hearing levels at

1000, 2000, and 3000 Hz.

4. The point at which the average of hearing losses in the stated three frequency range of 1000 - 3000 Hz begins to have a detrimental effect on the ability to understand speech is 25 dB re ANSI (1969).

With reference to the determination of hearing impairment (1. above), the ability to "hear" speech, measured in terms of the lowest intensity at which a listener can barely identify speech materials, provides little information concerning communication difficulties under everyday conditions. As Sataloff[98] states, "It [occupational deafness] implies the presence of obvious difficulties in hearing speech. Actually, the difficulty more often lies not so much in 'hearing' speech as in 'understanding' it." Furthermore, Davis and Silverman[99] observed that ". . . a man with severe high-tone nerve deafness (as is seen in occupational noise induced hearing loss), will always fail to hear certain sounds and will never make a perfect articulation score. On the other hand, the same man may hear some words, the easy low-frequency words, as well as anyone else does. He may have a normal threshold for speech."

This issue is further clarified if one compares the "typical" clinical picture of a person having a conductive hearing loss versus a person having a sensorineural hearing loss resulting from noise exposure. Both cases would be expected to have elevated speech reception thresholds (a measure of hearing for speech); however, in the case of the conductive loss, speech discrimination (measure of understanding) would be approximately the same as that for a person having normal hearing, provided that the presentation level is sufficiently above the speech reception threshold level. The person with occupational hearing loss (sensorineural), on the other hand, would have relatively poor discrimination scores, and the effect of raising the presentation level to higher levels often serves to reduce the articulation score[100] (see example in Figure 11). In applying the AAOO-AMA formula to the cases shown in Figure 11 it is possible that both would be rated identically in terms of hearing impairment, yet the sensorineural case has much more difficulty in understanding speech than does the conductive case. It is apparent, therefore, that the formula applied to compute hearing impairment should consider discrimination ability and that the pure tone frequencies used in the formula should be highly correlated with this latter function.

With reference to <u>speech communication under everyday conditions</u> (see 2 above), it has been assumed by the AAOO - AMA formula that the "ability to hear sentences and repeat them correctly in a quiet environment is taken as satisfactory evidence for correct hearing of everyday speech."[15,95] According to Kryter[88] this definition of everyday speech employs a type of speech material and a listening condition which is not indicative of everyday conditions and one which is "least likely to show any impairment in the deafened person."

Actually, everyday communication is placed under a wide variety of environmental stresses. Estimates of the amount of time that everyday speech is distorted range from a conservative figure of 50%[100] up to about 100%.[101] Furthermore, everyday speech rarely takes the form of complete sentence communications; thus, the number of speech cues available for accurate speech perception under everyday conditions is greatly reduced.[88] From this discussion, it may be concluded that an appropriate predicting scheme for determination of hearing impairment must include some consideration for an actual daily communication environment rather than some optimum condition as suggested by the AAOO - AMA.

With reference to predicting ability to understand speech on the basis of heavy levels at the pure tone average at 1000, 2000, and 3000 Hz (point 3 above), results of several studies indicate that hearing levels at these three frequencies predict hearing loss for speech under mild conditions of distortion better than the three frequency average at 500, 1000, and 2000. Mullins and Bangs,[102] investigating the relationship between speech discrimination and several indices of hearing loss, found that the pure tone hearing losses at 2000 and 3000 Hz had the highest correlation with speech discrimination. Harris, Haines, and Myers[103] studied the effect speeded speech had on discrimination in subjects with high frequency sensorineural hearing loss. They concluded that a nearly normal audiogram at 3000 Hz was essential for high sentence intelligibility if the speech material is distorted by increasing the speech rate. It was further concluded that once hearing losses progressed to include 2000 Hz, the effect on discrimination of speeded speech was quite devastating.

Kryter, Williams, and Green,[17] in a study of the effects of background noise on speech discrimination, found that in 114 adult male soldiers who had varying degrees of sensorineural hearing loss, threshold levels at 2000, 3000, and 4000 Hz correlated best with speech discrimination loss. They concluded, however, that the average hearing loss at 1000, 2000, and 3000 Hz should be used to predict speech hearing loss since this average represented a "reasonable compromise" for the results of the various studies which have dealt with the topic.

In a comparison of normal hearing subjects and subjects with sensorineural hearing losses on several different measures of hearing acuity, Ross et al.[104] found that in the impaired hearing group: (1) Speech discrimination scores in quiet tended to be poorer as the losses at 2000 and 4000 Hz increased and (2) neither pure tone threshold at 500 Hz nor speech reception threshold levels were related to speech discrimination in quiet.

Furthermore, in 1965 Harris[16] conducted an investigation to explore the effects of audiometric losses on discrimination scores for speech which was mildly and severely distorted. The results of this study indicated the frequency regions of greatest impact on intelligibility were somewhat different depending upon the severity of the distortion. However, Harris concluded that ". . . the region 2000 Hz and below is inadequate for predicting intelligibility of speech in noise, and that a point of vanishing returns is reached by adding anything beyond 3000 Hz."

Recently, Acton[105] investigated the effect of different signal-to-noise ratios on speech discrimination in a group of industrial workers who had incurred characteristic noise induced hearing losses. Results indicated that a significant loss in speech intelligibility occurred when high frequency hearing loss involved the 2000 Hz audiometric test frequency, and quite profound effects upon intelligibility once the loss had progressed to 1 KHz. In another recent investigation[106] of speech discrimination in industrial employees, it was found that hearing level at 2000 Hz had the highest correlation with speech discrimination (0.769, P 0.0001) under the most favorable condition of signal-to-noise (S/N = +10).

In summary, it is evident that in order to accurately assess hearing loss for speech under everyday conditions by means of pure tone hearing loss, a modification in the three frequency average recommended by the AAOO and the AMA is warranted. Such a modification should include the elimination of 500 Hz from the formula, and the addition of 3000 Hz in its place.

With reference to the level of beginning hearing impairment for speech (see 4 above), it would appear that an average hearing level of 25 dB re ANSI(1969) at 1000, 2000, and 3000 Hz signals the beginning of speech communication difficulties in everyday situations. In a comprehensive review of the topic of hearing impairment, Kryter[88] constructed several curves (see Figure 12) which related pure tone hearing level average to speech impairment for various samples of speech presented at different levels in quiet. As may be seen from this figure, the AAOO-AMA definition of impairment (Avg. HL at 500, 1000, and 2000 Hz of 25 dB re ANSI(1969)) allows for negligible impairment for sentences presented at an "everyday" level or normal conversational level, and only 15% impairment in the perception of isolated words presented at the weak conversational level.

Kryter, Williams, and Green[17] found that in subjects with sensorineural hearing losses, a dramatic change in perception of speech occurred as the average hearing level at 1000, 2000, and 3000 Hz shifted from approximately 18 dB re ANSI(1969) to about 31 dB re ANSI(1969). Corresponding to these shifts in average hearing level, sentence intelligibility in a mild background of noise (S/N = +5) dropped from 90 to 78% whereas PB work intelligibility, with slightly less noise (S/N = +10), decreased from 75 to 58%.

Results of the study conducted by Acton[105] concerned with speech intelligibility in a group of industrial workers indicated that a significant, although slight, shift in speech intelligibility (compared with normals) occurred when the hearing level (group mean) at 2000 Hz had reached 25.3 dB. At this point the average hearing level at 1000, 2000, and 3000 Hz was 25 dB re ANSI(1969).

Temporal Characteristics of Exposure

The damage risk criteria in Table IX are specifically concerned with limits of safe exposure to continuous noise for five hours or more. It has long been recognized that the ear can tolerate greater amounts of energy provided that the exposure time is limited.[73,74,107] Furthermore, research indicates that noises which are interrupted on a regular or irregular basis are much less hazardous to hearing.[109-111]

The decision as to how much noise can be tolerated for daily short-duration continuous exposures and interrupted exposures ultimately depends upon how the ear integrates noise over time. Probably the two most popular theories on how the ear responds to such stimulation are the equal energy and the equal pressure rules.

The equal energy rule states that equal quantities of acoustic energy entering the ear canal are equally injurious, regardless of how they are distributed in time. This rule dictates that, as exposure time doubles, the level of noise must be reduced by 3 dB in order to maintain an equal degree of hazard. The equal pressure rule, on the other hand, hypothesizes that the ear integrates noise on a pressure, rather than an energy basis. Such a rule maintains that for each doubling of the exposure time the level of noise must be reduced by 6 dB to maintain an equal degree of hazard.

Research attempting to determine which rule is appropriate has generally been inconclusive. Spieth and Trittipoe,[112] investigating the effects of high level, short duration exposures in human subjects, found that two different exposures would produce the same TTS if one exposure were 6 dB lower and twice the duration of the other. Conversely, Ward and Nelson[113] recently found that four separate exposure conditions, equated in terms of equal energy, all caused about the same amount of temporary threshold shift in chinchillas. However, they cautioned that their findings were only applicable to continous exposures and not to intermittent exposures.

Variables that are germane to interrupted exposures but do not play a significant role in limiting hazard from short-term continuous exposures further complicate the problem of how the ear responds and integrates noise over time. One such variable is the "acoustic" or "middle ear" reflex. When the ear is exposed to loud noise, the middle ear muscles contract, thus altering the impedance of the middle ear. This reflex, which serves to attenuate the noise reaching the inner ear, adapts out or disappears quickly if the noise is continuous and relatively unchanging over time. However, if the noise level varies considerably or is interrupted on a regular or irregular basis, then the reflex is sustained.

A second variable which plays an important role in reducing the hazard of interrupted noises relative to short-term continuous noises concerns the off-time of the exposure cycles. Depending upon the over-all level of the noise and the nature of the relationship between on-time and off-time, a considerable reduction in the degree of temporary hearing threshold shift may be observed.

To date, the only empirical data available on permanent hearing losses resulting from intermittent exposures comes from a study of iron ore miners conducted by Sataloff et al.[114] Their findings indicated that intermittent noises had to be some 15 dB more intense than continuous noises to cause the same additional hearing impairment in men ages 30 to 50 years. Although this evidence confirms the general notion that intermittent exposures are less hazardous than continuous steady-state exposures of the same duration and noise level, the applicability of this rule to other schedules of intermittency must await further investigation.

Since 1960, several damage risk criteria have been proposed to limit exposure to intermittent noise.[82,107,115] For the most part, these criteria, like the rules for assessing intermittent noise exposure discussed below, have been based predominantly upon evidence collected from studies of temporary threshold shift.

At least three different rules have been proposed in order to assess the hazard of exposures to intermittent noise. The first of these rules, developed by Ward et al.[28] was called the "on-fraction" rule. This rule states that the amount of temporary threshold shift resulting from a given intermittent exposure can be determined on the basis of noise level and average on-fraction (the time the noise is on divided by the total duration of exposure). This procedure assumes that levels below 75 dB SPL are not hazardous to hearing; thus, the amount of on-time is taken as the total time the noise is above 75 dB SPL. In a critical test of the on-fraction rule, Selters and Ward[111] found that this rule was invalid when the regular on-off times exceeded two minutes.

For burst durations longer than two minutes, a second rule has been suggested. This second rule, developed by Ward et al.,[109] is called the "exposure equivalent" rule. According to the concept of exposure equivalency, the amount of hearing change observed at the end of the day may be computed as follows:

a. Calculate the amount of TTS resulting from the exposure to the first bursts of noise.

b. Using generalized recovery curves, compute the residual TTS remaining at the end of the "off-time."

c. Determine how much exposure (time) to the noise causing the initial TTS in (a) above is necessary to cause the residual TTS.

d. Add the time in (c) above to the time of the subsequent noise burst and predict the TTS_2 at the end of the second exposure.

e. Repeat steps (b), (c), and (d) for each cycle in the daily exposure. The essential feature of this approach is that residual TTS is translated into exposure time.

One of the crucial assumptions of the "exposure-equivalent" rule is that the course of recovery from TTS is independent of the type of noise that produce the TTS. In a recent article, Ward[33] has presented data that question the validity of this assumption. It appears that intermittent exposure to high level, high frequency noise causes a considerable delay in the recovery of TTS relative to intermittent low frequency exposures.

A third approach in determining hazard from interrupted noise has been to determine the total on-time of the noise, regardless of how the noise bursts are distributed in time, and to consider the intermittent exposure in terms of an equivalent continuous exposure. This approach attempts to take into consideration the reduced hazard of interrupted noise by adjusting the rule which relates noise level and exposure duration. Although possibly not as scientifically rigorous as the previously mentioned procedures, the "equivalent continuous" rule is not constrained by the assumption concerning the regularity of exposure cycles which is basic to the other rules.

Intermittent noise exposure criteria based upon the first and/or second rules include those developed by Glorig, Ward, and Nixon,[115] CHABA Working Group 46,[107] and Botsford.[82] Botsford's intermittency criteria reflect a simplification and consolidation of the CHABA continuous exposure, long-burst intermittent, and short-burst intermittent contours into one general figure relating dBA level, total on-time (noise level above 89 dBA), and number of exposure cycles (see Figure 13). The limits of intermittent exposure expressed in these contours (shown in Table X) have recently been adopted by the Second Intersociety Committee.[27] Similar limits have been adopted as part of a revision of the German document concerned with assessment of industrial noise in working areas.[116]

Recent research designed to investigate the efficacy of the limits proposed in Table X have generally shown that the limits do not accurately predict risk to hearing, at least so far as temporary threshold shift is concerned. In a laboratory study[117] designed to evaluate selected exposure conditions from Table X, it was found that (1) the table shows concentrations of noise exposure within an eight-hour workday than can cause excessive amounts of temporary threshold shift and (2) the conditions did not yield equal effects on hearing, thus not affording equal protection. Conversely in a study of forestry employees[118] it was found that although the noise exposures were rated as hazardous according to Table X, the audiometric results indicated that the exposures did not pose a risk to hearing.

Considerably more data must be collected to evaluate present criteria which attempt to designate safe levels of exposure to intermittent noise. Furthermore, additional research is needed to define the relationship of exposure level and duration. Until such information is made available, a change in the present 5 dB rule for halving or doubling of exposure time and a change in the assessment of intermittent noise in terms of equivalent continuous exposure is unwarranted.

One variable which does warrant alteration concerns the lower level or "off" level of noise in intermittent exposures. The designation of such a level implies (1) noises below this level do not of themselves cause any significant temporary or permanent hearing threshold shift and (2) in combination with intermittent high levels of noise, optimum recovery may take place between noise bursts.

Various noise "cut-off" levels have been suggested. As mentioned previously, Glorig, Ward, and Nixon,[115] based on results of continuous noise exposure on temporary threshold shift, designated 75 dB SPL in any octave band as the level at which no TTS_2 would develop. The CHABA Working Group 46,[107] on the other hand, suggested that the "off" level was frequently dependent. For example, the safe level of exposure for the octave band 300 - 600 Hz was seen to be 89 dB SPL, whereas it was approximately 85 dB SPL for octave band 1200 - 2400 Hz.

Recently, Botsford[82] computed a dBA equivalent from the octave band damage risk criteria developed by CHABA. The results of this computation suggested that the "off level" based upon one-third octave or octave band sound pressure level will, in many cases, be below the level designated by Botsford (particularly in the case of strong narrow band components in the noise). Both the CHABA and Botsford criteria do not appear to be in accord with the intended meaning of a safe intermittent level in that present data suggest that there is a significant increase in the proportion of the population having hearing impairment in those groups exposed to continuous noise levels at and slightly below 85 dBA as compared with a non-noise exposed population.

Two lines of evidence suggest that the lower limit of interrupted exposure is considerably below the levels mentioned above. In a review of much of the available TTS and PTS data, Kryter[88] stated that a level of 65 dBA would cause "(a) no more temporary threshold shift than 0 dB for frequencies up to 2000 Hz and 10 dB for frequencies above 2000 Hz, measured two minutes after initial exposure for the average normal ear, and (b) a like amount of permanent noise-induced threshold shift following 20 years of nearly eight hours of daily exposure to noise in the hearing of no more than 25% of the population." Furthermore, results of a study[119] which investigated interrupted exposures using three different quiet levels indicated that the interval level of 57 dBA had a significant effect on the resultant TTS_2, TTS_{30}, and 30 minute recovery rate when compared with 67 dBA and/or 77 dBA interruption levels. It was concluded that recovery from intermittent noise exposure is maximized in quiet levels below 67 dBA.

It would appear from the foregoing discussion that a level of approximately 65 dBA meets the requirements of criteria established for a true "off-level" for intermittent exposure.

Support of the Standard

To comply with the protection goal of the NIOSH standard (see Part VI), hearing impairment for an individual is considered to occur when the average of hearing threshold levels at the three audiometric frequencies 1000, 2000, and 3000 Hz for both ears exceeds 25 dB (Thresholds re ANSI S3.6 (1969)). As described below, NIOSH noise and hearing study data relevant to hearing impairment were analyzed, and the incidence of hearing impairment of noise exposed employee groups was compared with that of exposed employee groups of comparable age and work experience. For the purposes of this part, noise-exposed employees are those exposed to 80 dBA-Slow to 102 dBA-low and non-noise-exposed employees are those exposed to less than 80 dBA-Slow. These comparisons resulted in the risk values applicable to the NIOSH standard (incidence of hearing impairment of exposed group minus incidence of hearing impairment of unexposed group).

Data collected from 1968 to 1971 by NIOSH, represented the steelmaking, paper bag processing, aluminum processing, quarrying, printing, tunnel police, wood working, and trucking employees included in 13 noise and hearing surveys. Audiometric data from non-noise exposed employees were collected in 12 of these 13 surveys. The audiometric data were analyzed using the current "fence" of hearing handicap, 25 dB average hearing threshold level at 0.5, 1, and 2 kHz (thresholds re ANSI S3.6 (1969), as well as the fence appropriate to this document, 25 dB average hearing threshold level at 1, 2, 3 kHz (thresholds re 1969 audiometric zero). The total sample of more than 4000 audiograms, however, could not be used to represent a qualitative measure of hearing loss. Employees not exposed to a specified continuous noise level in dBA-Slow over their working lifetime and those with abnormal hearing levels as a result of their medical history and a variety of otological problems were eliminated from the sample. Thus, 1172 audiograms were used which represented 792 noise-exposed and 380 non-noise exposed employees. The distribution of employees with respect to noise exposure, age, and experience is listed in Table XI.

The audiometric van used for the hearing tests was capable of testing six individuals at one time. All employees were tested before the beginning of their work shift, and, due to scheduling problems, the number of employees in a test session ranged from one to six. When less than six employees were present at a testing session, an attempt was made to randomize the assignment of audiometers. It was also necessary to use headphones with otocups to properly shield the employees from the possible effects of interference caused from hearing the other test tones in the van. However, it was found from the results of two independent studies in the NIOSH laboratory that there was no significant difference in measured thresholds between headphones fitted with otocups and those fitted with standard MX-41/Ar type ear cushions.

Before data analysis could be done, it was necessary to check the calibration data accumulated during the respective survey. Calibration of the audiometeres used to take the audiograms was usually performed before and after each survey. The data were corrected where necessary to the appropriate values given in the American National Standard Specifications for Audiometers, ANSI S3.6 (1969).

Used for purposes of data analysis were the three-frequency averages mentioned above in the definitions of hearing impairment. HLI $(\overline{0.5, 1, 2})$ and HLI $(\overline{1, 2, 3})$ are used to denote these averages performed over both ears. (HLI stands for "hearing level index.")

The samples were grouped into age and experience ranges to assure equal numbers per cell and a consistent spread of the data across the various dBA levels.

The following lists the steps made in the data analysis:

1. Hearing level indices for 87 and 94 dBA noise exposed individuals were grouped into 31 samples for three-way cross-classification with respect to dBA level, age group, and experience group. The data were transformed by taking natural logarithms, and the resulting variances of log HLI $(\overline{0.5, 1, 2})$ and log HLI $(\overline{1, 2, 3})$ were computed for each sample. For each of the two dBA levels, Bartlett's tests for homogeneity of variances were performed over all age and experience combinations. Separate tests were performed for HLI $(\overline{0.5, 1, 2})$ and HLI $(\overline{1, 2, 3})$ average noise indices. Of the four Bartlett's tests, three showed no suggestion of nonhomogeneity of variance, but the fourth was significant at the 0.05 probability level. However, only one atypical variance was found within the "nonhomogeneous" group, and this was believed to be caused by an improbable combination of purely random variations and not indicative of a real elevation of variability for the cell in question. Thus, the conclusions were that variability of log HLI $(\overline{0.5, 1, 2})$ and log HLI $(\overline{1, 2, 3})$ for replicate subjects was stable over all cells defined by the cross-classification.

2. Fifth-degree orthogonal polynomial regression curves were fitted to log HLI vs. dBA for each age and experience cell using data for <u>all</u> dBA levels. Significance tests for nullity of regression coefficients were performed. For most of the curves which exhibited any significant trend, a straight line fitted the data within the limits of unexplained variability.

In several cases, fourth or fifth degree coefficients showed significance, but examination of the plotted points revealed these to be artifacts due to clustering of the dBA levels for those plots, i.e., too few levels of the independent variable so that the polynomial tended to "fit the random errors."

3. Histograms of pooled deviations of log HLI values from the respective regression lines for HLI$(\overline{0.5, 1, 2})$ and HLI $(\overline{1,2,3})$ were constructed by fitting normal distribution curves. Chi-square goodness-of-fit tests were performed. The tests revealed that the log HLI deviations from the means were normally distributed over the full range of variability to a very significant degree of approximation as shown in Figures 14 and 15 Means were found to be zero, and pooled variances were calculated for use in later stages of the analysis.

4. Regression lines for different age groups within an experience-level were tested for parallelism, and in every case, the lines were found to be parallel within the limits of error in the slope estimates. Pooled slopes were calculated, and the intercepts were revised to reflect the small differences between the separate and pooled slopes. Families of parallel lines were plotted. Tests for coincidence of sets of parallel lines were then made by the method of covariance analysis. This revealed significant difference at the 0.01 probability level in all cases.

5. Regression lines for different experience levels within an age group were not found to be parallel, and, for each age group, the intercepts were compared by means of Student's t-tests. The "intercepts" were defined as ordinates of the regression lines at a dBA of 79, which represented the control group exposed to less than 80 dBA. These regression lines were found to be significantly different families of nonparallel lines from common intercepts.

6. For each age and experience combination, the normal distribution of pooled variation in replicate subjects was distributed about the regression line with its zero mean centered at the ordinate of the line. This model was then used to calculate a predicted percentage of subjects whose hearing levels exceeded a "fence". Thus, such percentages could be tabulated as a function of dBA for each age and experience category. Furthermore, risk values were then derived as the percentage difference between employees exposed to noise levels 80 dBA or greater and those exposed to less than 80 dBA (Table XII and XIII).

This analysis indicates that the 85 dBA-Slow noise limit for an eight-hour day, in conjunction with the medical program prescribed in the standard, will improve the protection of the working population from hearing loss that could impair their abilities to understand everyday speech. The reliability of the analysis is evidenced by homogeneity of the variance and normality of the population distributions. In other words, the evaluation is repeatable and is representative of a random sample.

Comparison of NIOSH Data with Other Published Data

Three analyses comparable to the NIOSH analysis use a definition of hearing impairment different from that used in the NIOSH standard. In order to compare NIOSH data with these analyses, the NIOSH data was analyzed using the following definition: hearing impairment is considered to occur when the average of the hearing threshold levels at the audiometric frequencies 500, 1000, and 2000 Hz for both ears, HLI $(\overline{0.5, 1,2})$, exceeds 25 dB (thresholds re ANSI S3.6 (1969)). Again, risk is defined as the additional incidence of hearing impairment of noise exposed worker groups when compared with that of equivalent nonnoise exposed groups, or the difference between the two incidences.

NIOSH risk data for retirement age groups are compared in Tables XIV, XV, and XVI with the following sets of risk data: (1) that used by the American Conference of Governmental Industrial Hygienists,[85] the OSHA Federal Standard,[86] as well as the Intersociety Committee;[27] (2) that used by the International Organization for Standardization (ISO); and (3) that developed by the National Physical Laboratory (U.K.).[89] In all cases, the age grouping and sound levels are similar to those of the NIOSH data.

The Intersociety Committee, composed of representatives from the American Academy of Occupational Medicine, American Academy of Opthalmology and Otolaryngology, American Conference of Governmental Industrial Hygienists, Industrial Hygiene Association, and Industrial Medical Association, in 1970, published an analysis similar to the NIOSH analysis. It studied a combination of several noise and hearing studies[120-124] in order to determine risk from noise exposure. There are several features of this analysis, however, which differ from that by NIOSH.

First, most of the Intersociety data consisted of hearing levels for only the right ear. Although the right ear may statistically be better than the left, both ears were used in the NIOSH analysis in order to obtain a more realistic incidence of hearing impairment since a person hears with both ears, not one. This same feature of the Intersociety analysis is discussed by Botsford[125] who determined that the use of the average of the two ears produces a higher risk factor.

Also, the Intersociety data were not separated into experience groups within each age group. The NIOSH analysis found that work experience ranged from 0 to 40 years in the older age groups, and thus, it was necessary to classify employees by experience as well as by age.

Moreover, some of the studies used in the Intersociety analysis used Speech Interference Level SIL: the average of octave band levels with center frequencies 500, 1000, and 2000 Hz) as the measure of exposure in analyzing the noise levels encountered by the employees. NIOSH considers this unsatisfactory since the conversion of SIL to dBA is generally inaccurate and is based on tenuous assumptions.

Finally, the Intersociety analysis used the noise-exposed populations from a variety of different studies with one non-noise exposed population and one "general" population (including both noise exposed and non-noise exposed individuals) for their composite determination of risk. Furthermore, the different investigations used in this analysis were each unique with respect to screening (or excluding) criteria, audiometric equipment, and data analysis. The NIOSH study used a non-noise exposed population which consisted of a pool of employees similar in these respects to each other and to the noise exposed population under study.

Thus, the Intersociety analysis differs from that of NIOSH in several characteristics: use of one ear only, nonseparation of experience groups, use of SIL in noise levels, and use of a dissimilar composite population. Some of these characteristics tend to produce lower risk values and considerably more uncertainty than the NIOSH analysis, as evidenced in Table VII-3.

Another study whose analysis determined risk is published in ISO Recommendation R1999 (1971).[90] This analysis differs from the NIOSH analysis in three ways. The first is that only the right ear was used. The second is that no separation of age groups into work experience groups was done. The third is that no screening for otological abnormalities was done in the ISO study. On the other hand, the entire sample of data used in this analysis is homogeneous in that all members of the sample were taken from one comprehensive examination.[126] The lack of otological screening has some effect on incidence of hearing impairment for both the noise exposed and the non-noise exposed groups, but, when risk is calculated by subtracting the two incidences, the effect is essentially cancelled. Thus the NIOSH risk values are very similar to the ISO values, as evidenced in Table XV.

Another study, by the British National Physical Laboratory,[127] developed an equation for calculating hearing levels of the populations exposed to noise. This equation was used by Robinson[89] to develop risk tables for various groups and noise levels.

In comparing the British risk values with those of the NIOSH, shown in Table XVI, it can be seen that the British risk values are much lower. The nature of this discrepancy is difficult to determine; however, it may result from the severity of the British screening for otological abnormalities and previous noise exposure. It is also possible that the reason for the discrepancy is the baseline, or reference level, used in this analysis. The British used a baseline (which they considered to be audiometric zero), determined by a non-noise exposed industrial group of people 18-25 years of age, which was actually lower than audiometric zero (thresholds re ANSI 1969 (or ISO R389)). It has been found, however, in many United States studies[5,21,22,126,128,129] including the NIOSH analysis, that the average hearing threshold level over the audiometric frequencies 500, 1000, and 2000 Hz (HLI($\overline{0.5, 1, 2}$)) is 5 - 10 dB (thresholds re ANSI S3.6-1969) for non-noise exposed employees 18-25 years of age, which is approximately 10 dB higher than that of the 97 non-noise controls used by the British. Thus, if the British data are used to calculate risk with a 10 dB correction, which brings the baseline of their data into coincidence with the baseline appropriate to the protection goal of this standard and which is representative of the baseline found in occupational environments in many U.S. studies, then the risk values using the British data are, in fact, very similar to those found in both the NIOSH and ISO risk tables, as shown in Table XVI.

The "Hygiene Standard for Wide-Band Noise" of the British Occupational Hygiene Society[87] is based on assumptions radically different from those of the NIOSH standard. As mentioned previously, the British consider hearing impairment to occur when the average hearing loss at the audiometric frequencies 500, 1000, 2000, 3000, 4000, and 6000 Hz for both ears exceeds 40 dB [(threshold re ISI R389-1964)] (48 dB minus 8 dB for presbycusis or aging effects). This 48 dB "fence" is comparable to an HLI ($\overline{0.5, 1, 2}$) of approximately 39 dB for thresholds re ANSI S3.6 (1969). Such a high fence is not in line with the protection goal of the NIOSH standard.

Effect of Hearing Impairment Definition on Risk

The NIOSH standard was based on risk calculated using the definition of hearing impairment as the condition when the average of the hearing threshold levels at the three audiometric frequencies 1000, 2000, and 3000 Hz, HLI

$(\overline{1, 2, 3})$ for both ears exceeds 25 dB [(thresholds re ANSI S3.6 (1969)]. Another definition was used to compare the NIOSH risk data with other data. This definition was that hearing impairment for an individual is considered to occur when the average of the hearing threshold levels for the audiometric frequencies 500, 1000, and 2000 Hz, HLI $(\overline{0.5, 1, 2})$ for both ears exceeds 25 dB re ANSI S3.6 (1969). Some of the NIOSH risk values calculated using both definitions are shown in Table XVII. Although the incidences of hearing impairment are higher for the definition using HLI $(\overline{1, 2, 3})$, the risks due to noise are, in fact, quite similar. Thus, even though the two definitions reflect the incidence of hearing impairment in the population differently, the different definitions have little effect when risk is calculated.

Comparison of the NIOSH Standard with Other Standards

The present Federal standard for occupational noise exposure,[86] which is based on the same data as that of the Intersociety Committee, ACGIH, and Walsh Healey Public Contract Act mentioned above, differs in several respects from that of the NIOSH standard, and the analysis shows lower risk than does NIOSH for the same noise levels. Indeed, industrial employee data more recent than the Intersociety data, published as ISO R1999,[90] has shown trends comparable to those of the NIOSH analysis. Thus, the 85 dBA-Slow noise exposure level for a nominal eight-hour day should allow no more than an increase of 10-15 percentage points in the incidence of hearing impairment, as compared to the non-noise exposed population. (This statistic is for employees aged 50-65 years, having a minimum of 20 years noise exposure.)

The recommended occupational exposure level of 85 dBA for an eight hour day will be applicable to all newly designed installations six months after the effective date of the standard. However, the level of 85 dBA is not applicable to established installations until such time as determined by the Secretary of Labor in consultation with the Secretary of Health, Education and Welfare. Such a provision was necessary because of the lack of sufficient available evidence upon which to determine a reasonable time period for the development of technologically feasible methods to meet the 85 dBA level.