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THE RELATIONSHIP OF THE EXCHANGE RATE TO NOISE-INDUCED HEARING LOSS

by

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I. INTRODUCTION

Exposure to high levels of noise can be quite hazardous, completely harmless, or anything in between; the key to the outcome is exposure duration. For some time, scientists have attempted to identify the relationship between noise level and duration that will best predict hearing impairment. Currently, this relationship is called the "exchange rate," although other terms have been used to describe it, including the "doubling rate," "trading ratio," and "time-intensity tradeoff". The most commonly used exchange rates incorporate either 3 dB or 5 dB per doubling or halving of exposure duration.

The 3-dB exchange rate, which is used by the U.S. Environmental Protection Agency (EPA), Great Britain, and many European countries, is also known as the equal-energy rule or hypothesis, abbreviated L_{eq}. First proposed by Eldred et al. (1955), it was later supported and expanded by Burns and Robinson (1970). This hypothesis maintains that equal amounts of sound energy will produce equal amounts of hearing impairment, regardless of how the sound energy is distributed in time. Theoretically, this principle could apply to exposures ranging from a few minutes to many years. Ward and Turner (1982), however, suggest restricting its use to the sound energy accumulated in one day only. They make a distinction between an interpretation of the "total energy" theory that would allow a whole lifetime's exposure to be condensed into a few hours, and a restricted "equal-A-weighted-daily energy" interpretation of the theory. Burns (1976) also cautions against the misuse of the equal energy rule, noting that it was based on data gathered from individuals who experienced daily 8-hour occupational exposures for periods of months to years, and thus, extrapolation to very different conditions would be inappropriate.

The 5-dB exchange rate is sometimes called the OSHA rule, abbreviated L_{OSHA}, and it is somewhat less conservative than the equal energy rule. It attempts to account for the interruptions in noise exposures that commonly occur during the work day (OSHA, 1975), presuming that some recovery from temporary threshold shift (TTS) occurs during these intermittencies, and the hearing loss is not as great as it would be if the noise were continuous. The 5-dB rule *assumes* intermittency but does not *guarantee* it. The rule itself makes no distinction between continuous and non-continuous noise, and it will permit comparatively long exposures to continuous noise at higher sound levels than would be allowed by the 3-dB rule.

Several other methods of combining noise level and duration deserve mention. The equal pressure rule maintains that a 6-dB increase may be tolerated for each halving of exposure duration. Spieth and Trittipoe (1958) found that the 6-dB rule predicted TTS resulting from short-duration, high-level exposures somewhat better than the 3-dB rule, but it has not been generally accepted. The 4-dB rule, which is used by the U.S. Air Force (1982), may have been adopted as a compromise between 3 dB and 5 dB. It is supported by an unpublished study by Parrack, showing that the 4-dB rule best predicted hearing damage at the 1000-Hz audiometric frequency (Johnson, 1973). Saunders et al. (1977) put forward a method they call the "equivalent power" hypothesis, based on asymptotic threshold shift (ATS) data. Finally, some criteria, such as those developed by the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA), have varied the exchange rate according to noise level and temporal pattern (Kryter et al., 1966).

Most of the controversy over the exchange rate concerns its use in industrial noise environments whose levels vary over time. Evidence from the laboratory shows that intermittent exposures cause less damage than continuous ones, presumably because the ear is allowed some time to recuperate during the interruptions. However, there is some doubt about the extent to which laboratory intermittencies resemble those in the real-world. Also, the same intermittent exposure can produce different degrees of damage, depending on which effect one chooses to examine (temporary loss, permanent loss, or anatomical damage).

In discussing the effects of noise as it varies in time, it would be helpful to examine different definitions or ways of describing these temporal characteristics. Continuous noise levels vary only minimally as a function of time and are sometimes referred to as steady or steady-state. Noise that is not continuous is often popularly called "intermittent." But this non-continuous noise should actually be divided into two categories: "intermittent" and "varying." When these categories are not differentiated, they will be referred to in this report as "non-continuous."

Intermittent noise is characterized by large differences in sound level and periodic interruptions at relatively low levels. Varying noise can also have large differences between maximum and minimum levels, but levels in between are present for a considerable amount of time. Varying noise is sometimes referred to as "fluctuating" noise. Outdoor occupations, such as forestry and construction can often be considered intermittent noise exposures because the noise is interrupted by intervals at relatively low sound levels. Factory noise, on the other hand, is usually continuous or varying because of the proximity of numerous noisy operations and the presence of hard surfaces which produce reverberation and inhibit the decay in sound levels. Several definitions of intermittent and fluctuating or varying noise are given in Table I. Graphic examples of intermittent and varying noise are portrayed in Fig. 1 from Passchier-Vermeer (1973).

Most of the earlier investigations of the relationship between noise level and duration measured TTS in humans (eg. Eldred et al., 1955; Glorig et al., 1961; Kryter et al., 1966; Ward, 1960; Ward, 1970). TTS in humans and animals is usually stated in terms of the shift experienced two minutes after cessation of exposure (TTS_2), although sometimes investigators will report the shift experienced at various intervals during recovery (such as TTS_{30} or $TTS_{2\ hours}$). Later studies employed animal models so that permanent threshold shift (PTS) and cochlear damage could be assessed as well as TTS (eg. Bohne and Pearse, 1982;

Table I. Definitions of intermittent and fluctuating or varying noise.

Source	Intermittent Noise	Fluctuating or Varying Noise
Committee on Hearing, Bioacoustics, and Biomechanics (Kryter et al., 1966)	Individual noise bursts do not exceed 2 min and there is alternation between noise bursts and levels below EQ.[1]	Noise remains at a single level no more than 2 min and never drops below the 8-hr allowable level for a particular band or pure tone.
Dept. Labor, 1969 (Walsh-Healey noise standard)	Levels fall below 90 dB(A) (implied).	
Dept. Interior, 1970	Interruptions occur when levels fall below 80 dB(A) more than 5 minutes or when durations below 80 dB(A) are equal to at least 20 % of the preceding burst duration.	
Passchier-Vermeer, 1973	Difference of at least 20 dB between highest and lowest levels, with levels in between present for only negligible amount of time during period of observation.	Several sounds occur during period of observation and levels between highest and lowest are present for a considerable amount of time.
EPA, 1974a	Levels fall below 65 dB(A) for 10% of each hour. Peaks 5-15 dB higher than background.	
OSHA, 1981, 1983	Levels fall below 80 dB(A) (implied).	
ANSI S1.13, 1986	Noise levels equal ambient 2 or more times during period of observation.	Level varies but does not equal ambient more than once during period of observation.

[1] EQ = effective quiet. In this case the 8-hr allowable level for a particular band or pure tone.

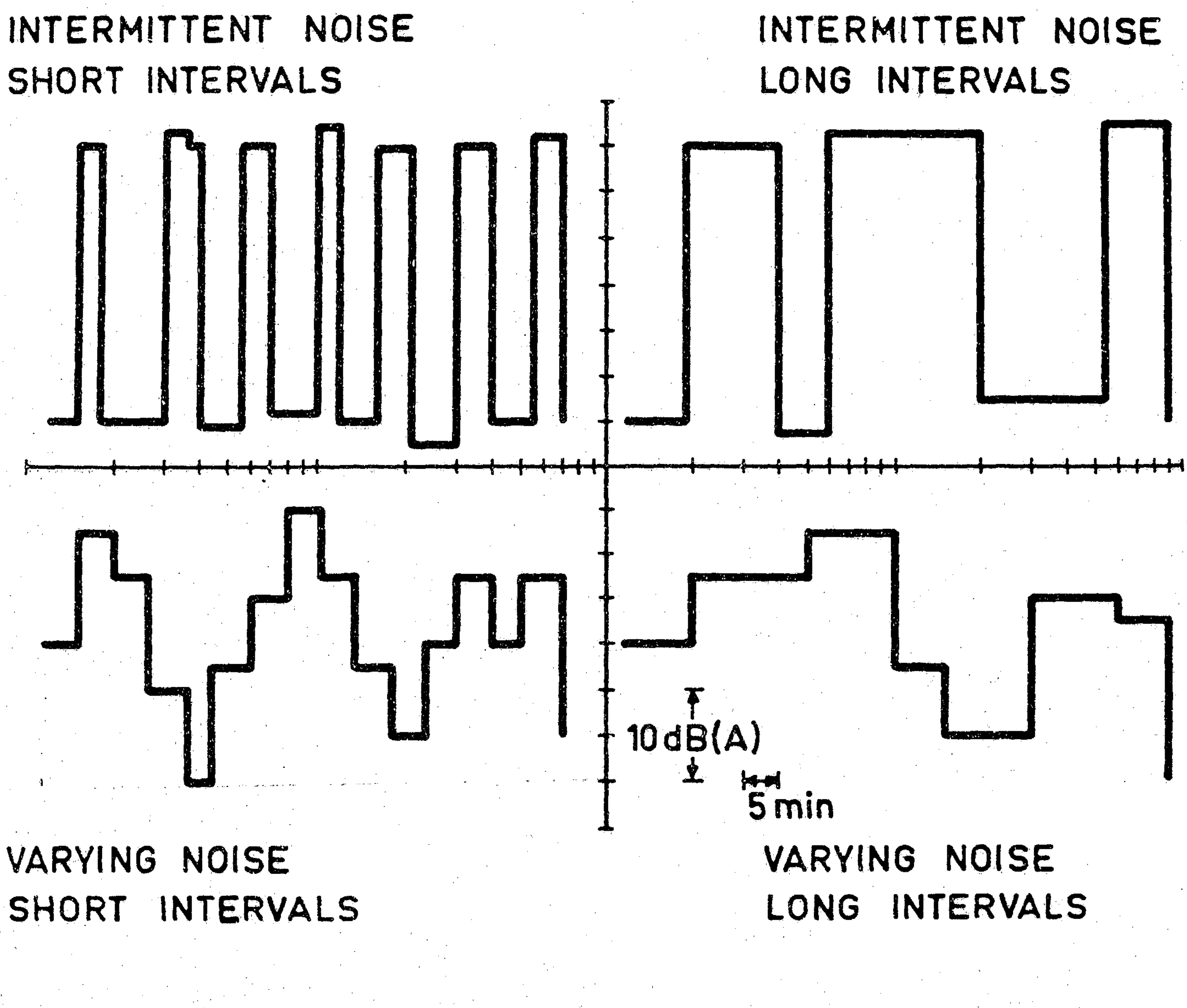

Fig.1. Illustration of Passchier-Vermeer's classification of two types of intermittent and varying noise. From Passchier-Vermeer (1973).

Ward and Nelson, 1971; Ward and Turner, 1982; Ward et al., 1983). The animal model used for noise and hearing loss investigations has usually been the chinchilla, which has the advantage of easy handling and long life. In recent years there has been considerable interest in another measure of TTS called asymptotic threshold shift (ATS), where threshold shift appears to reach an asymptotic level after 8 to 10 hours of continuous noise exposure and remains at this level indefinitely until the noise exposure is terminated. In addition, there have been several epidemiological field studies of noise-exposed workers (eg. Burns and Robinson, 1970; Evans and Ming, 1982; Holmgren et al., 1971; Johansson et al., 1973), but their conduct in recent years is limited due to the widespread use of hearing protectors.

One problem relating to the use of animal studies for the development of damage-risk criteria is that the degree to which we can generalize quantitatively to humans is always open to question. According to Miller (1970), the chinchilla's audibility threshold curve is quite similar to that of the human. However, it appears that chinchillas incur somewhat more hearing loss than humans for comparable exposures (Trahiotis, 1976). It has also been suggested that the chinchilla's recovery from noise is somewhat slower than that of humans. That being the case, permanent damage from repeated exposures would tend to accumulate more quickly and generalizations to the human condition should be made with some degree of caution. Ward (1984) reports that "the chinchilla has one of the slowest recovery processes among all the animals whose susceptibility to noise has been studied." But humans have also demonstrated various states of delayed recovery from TTS (Mills et al., 1970 and 1983; Johnson et al., 1976; Ward, 1970). For example, acting as his own subject, Mills was exposed to a 500-Hz band of noise at 92.5 dB for 19.5 hours (Mills et al., 1970). This exposure produced an ATS of 27.5 dB, from which it took 4 to 7 days to recover completely. The prevailing view in the research community is that while quantitative generalizations may not always be accurate, patterns or principles of hearing damage should apply (Erlandsson et al., 1987).

The selection of an appropriate exchange rate necessitates examining the growth of equal hearing hazard as a function of noise level and duration. This relationship depends upon numerous variables, including the measure of damage (TTS, ATS, PTS, or cochlear damage), the audiometric frequencies to be protected, and various temporal and acoustic parameters, such as the noise on-time and off-time and the level of "quiet" during interruptions. Because of these many variables, it appears that no single function will fit all conditions. Selection of any single exchange rate must, therefore, involve compromise. The key is to select one that most closely fits the hearing loss data within an acceptable range of noise levels and durations.

For purposes of this document, only continuous, varying, and intermittent exposure data will be discussed here. There is, however, some precedent for the application of a single exchange rate to all kinds of exposures, including industrial impacts and impulses as short as gunfire (EPA, 1974a; von Gierke et al., 1981; ISO, 1990; Martin, 1976).

II. CRITERIA AND STANDARDS

In examining the issues surrounding the exchange rate, it would be useful to trace the history of its evolution in criteria and standards for noise exposure.

A. Air Force

The earliest set of damage-risk criteria employing any exchange rate was published by the Air Force (Eldred et al., 1955). Allowable 8-hour levels were specified for octave bands, and for pure tones and critical bands. Increases of 3 dB were allowed for each halving of exposure duration. The justification for the 3-dB exchange rate came from animal experiments performed by Eldredge and Covell (1952) and from various TTS studies. These criteria formed the basis for the first military hearing conservation regulation, AFR 160-3 (1956), which also was used by other government agencies and industry.

B. ISO-1961

In the first major international attempt at noise exposure standardization, the International Organization for Standardization (ISO) proposed a draft standard for continuous noise with durations less than 8 hours using the 3-dB rule (ISO, 1961). A different method, portrayed in Fig. 2, was recommended for assessing the hazard of non-continuous noise, based on recommendations by Glorig et al. (1961). Permissible on-times are given for certain exposure levels (expressed in "noise rating numbers") as a function of the duration of off-times and the number of exposure cycles per day. The relationship between duration and level is curvilinear, with proportionally higher levels allowed as total durations, and especially as individual burst durations, become shorter.[1] The standard was never finalized in this form.

C. CHABA

In 1965 the National Academy of Sciences-National Research Council, Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) issued criteria for assessing allowable exposures to continuous, fluctuating, and intermittent noise in the form of octave and one-third octave bands of noise, and pure tones (Kryter et al., 1966). The relationship between duration and level for equally hazardous bursts of continuous noise is a curvilinear function, which is relatively shallow (2 to 3 dB per halving of duration) for long, moderate-level bursts, and accelerates rapidly (9 to 11 dB per halving) for high-level, short-duration bursts. Fluctuating noise is defined as conditions where the noise remains at a single level for no more than 2 minutes and the level never drops below

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[1] The same method for assessing exposure to intermittent noise was recommended in the report of the Subcommittee on Noise of the Committee on Conservation of Hearing of the American Academy of Ophthalmology and Otolaryngology (AAOO, 1964).

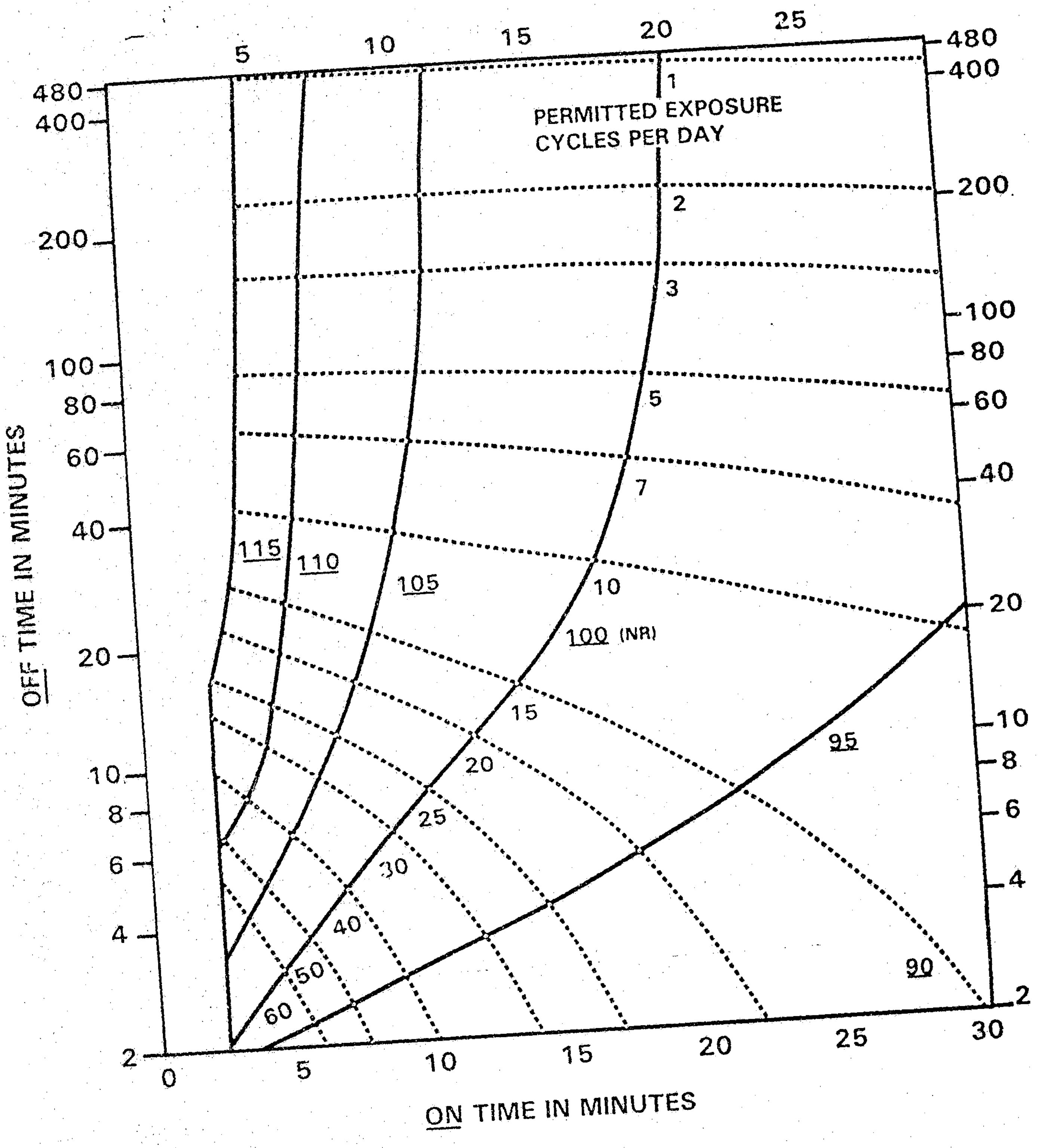

Fig. 2. Curves for rating non-continuous noise exposures. From Glorig *et al.* (1961).

"effective quiet," which is the 8-hour allowable level for that particular band or pure tone. To assess the hazard from fluctuating noise, one calculates the arithmetic average of sound pressure levels over the exposure period.

A different set of curves is provided for intermittent noise, which is defined as noise levels alternating throughout the day between bursts of 2 minutes or less and levels below effective quiet. One determines the "on-fraction," the relationship between burst duration and the duration of the burst-plus-quiet cycle, and then consults the diagrams to find the allowable level or duration of sounds in specific octave or third-octave bands for on-fractions of 0.4 to 1.0. The criteria allow higher exposure levels as durations become shorter and recovery periods become longer. The authors predicted that the allowable exposures would produce noise-induced permanent threshold shifts (NIPTS) after 10 or more years no greater than the following amounts in the median and in the more susceptible 20th and 10th percentiles of the exposed populations:

Frequency	Median	20th Percentile	10th Percentile
1000 Hz	10 dB	20 dB	30 dB
2000 Hz	15 dB	30 dB	45 dB
3000 Hz	20 dB	40 dB	60 dB

Hearing loss data for industrial workers were used to develop the long-duration, single-burst criteria, but TTS data were employed for the short-burst continuous and intermittent noise curves because of the lack of PTS data in this area.

In the development of its criteria, the CHABA committee used the following postulates:

1. TTS_2 is a consistent measure of the effects of a single day's exposure to noise.

2. All exposures that produce a given TTS_2 will be equally hazardous (the "equal temporary effect" theory).

3. NIPTS produced after many years of habitual exposure, 8 hours per day, is about the same as the TTS_2 produced in normal ears by an 8-hour exposure to the same noise.

In its report, the committee also cautions that there is little direct evidence to support the assumption of equal temporary effects (postulate 2 above) and that future working groups should carefully reevaluate it.

D. Botsford's Modification of CHABA

In 1967, Botsford published a simplified set of damage-risk criteria based on the CHABA curves, having observed that the CHABA method had proved too complicated for general use. He developed a statistical approach, based on typical manufacturing noises, to convert the octave-band curves to equally hazardous A-weighted levels. He also combined the long-burst, short-burst, and intermittent noise contours into one scheme. Fig. 3 shows Botsford's scheme, with permissible A-weighted exposure level plotted as a function of total duration and the number of exposure cycles. The method assumes that interruptions will be of "equal length and spacing so that a number of identical exposure cycles are distributed uniformly throughout the day". These interruptions would occur during coffee breaks, trips to the washroom, lunch, and periods when machines are temporarily shut down.

E. Intersociety Committee - 1967 and 1970

Also in 1967 the "Intersociety Committee" published damage risk criteria for noise exposure. This committee was composed of two members from each of five technical organizations and among them were Botsford and Glorig. Criteria for

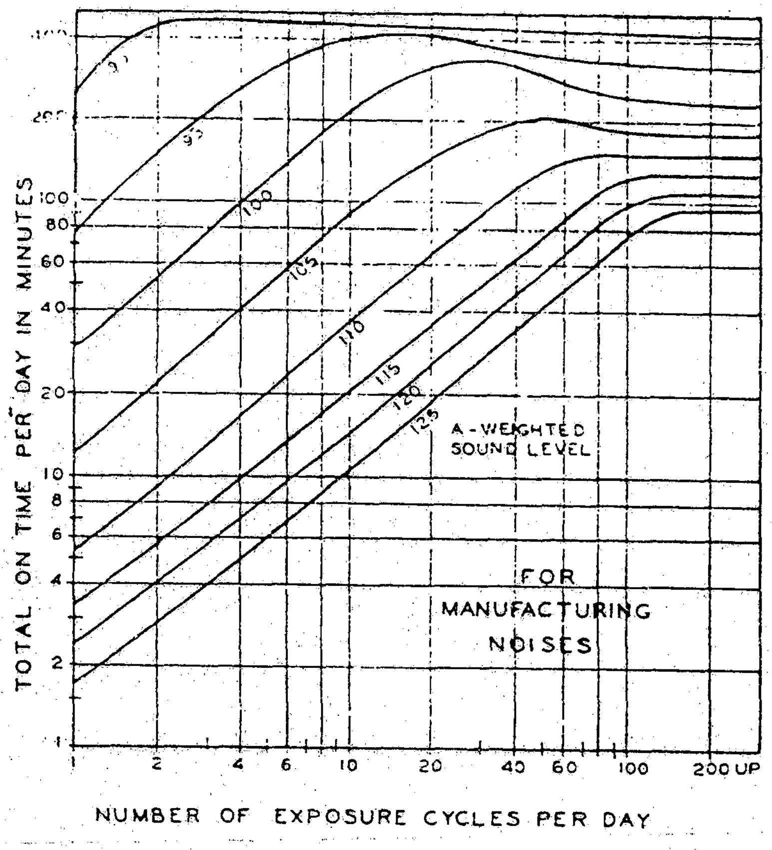

Fig. 3. Total duration of A-weighted sound levels allowable during an 8-hour day as a function of the number of periodic interruptions. From Botsford (1967).

continuous noise were given for age groups from 20 to 60 years exposed to noise levels from 85 to 104 dB(A). Criteria for non-continuous ("intermittent") noise were based on TTS studies, presumably the same studies that had been used in the development of the ISO, CHABA, and Botsford criteria. Fig. 4, from the Intersociety's 1967 report, shows curves that are quite similar to the ones originally proposed by Glorig et al. (1961) and included in the ISO proposed standard (1961), but the criteria for permitted numbers of cycles have been omitted. The Committee states that the information contained in Fig. 4 "may be approximated by the simple rule that for each halving of daily exposure time, the noise levels may be increased by 5 dB up to a maximum of 115 dB average of the three octave bands 300-2400 cps (122 dB(A)), without increasing the hazard of hearing impairment". Like Botsford's scheme, this scheme also assumes uniform off-times.

In 1970 the Intersociety Committee revised its criteria. This time the graph for assessing non-continuous noise exposure was replaced with a table showing permissible exposure levels (starting at 90 dB(A)) as a function of duration and the number of occurrences per day. Again, exchange rates vary considerably depending on noise level and frequency of occurrence. For continuous noise with durations less than 8 hours, the Committee recommended maximum exposure levels based on a 5-dB exchange rate.

F. Walsh-Healey Noise Standards

In 1968 the Department of Labor proposed a noise standard under the authority of the Walsh-Healey Public Contracts Act (Dept. Labor, 1968). The proposal contained a permissible exposure limit of 85 dB(A) for continuous noise. Exposure to non-continuous noise was to be assessed over a weekly period according to a large table of exposure indices. Again, the exchange rate varied according to level and duration; a rate of 2 to 3 dB was used for long-duration noises of moderate level, and 6 to 7 dB for short-duration, high-level bursts.

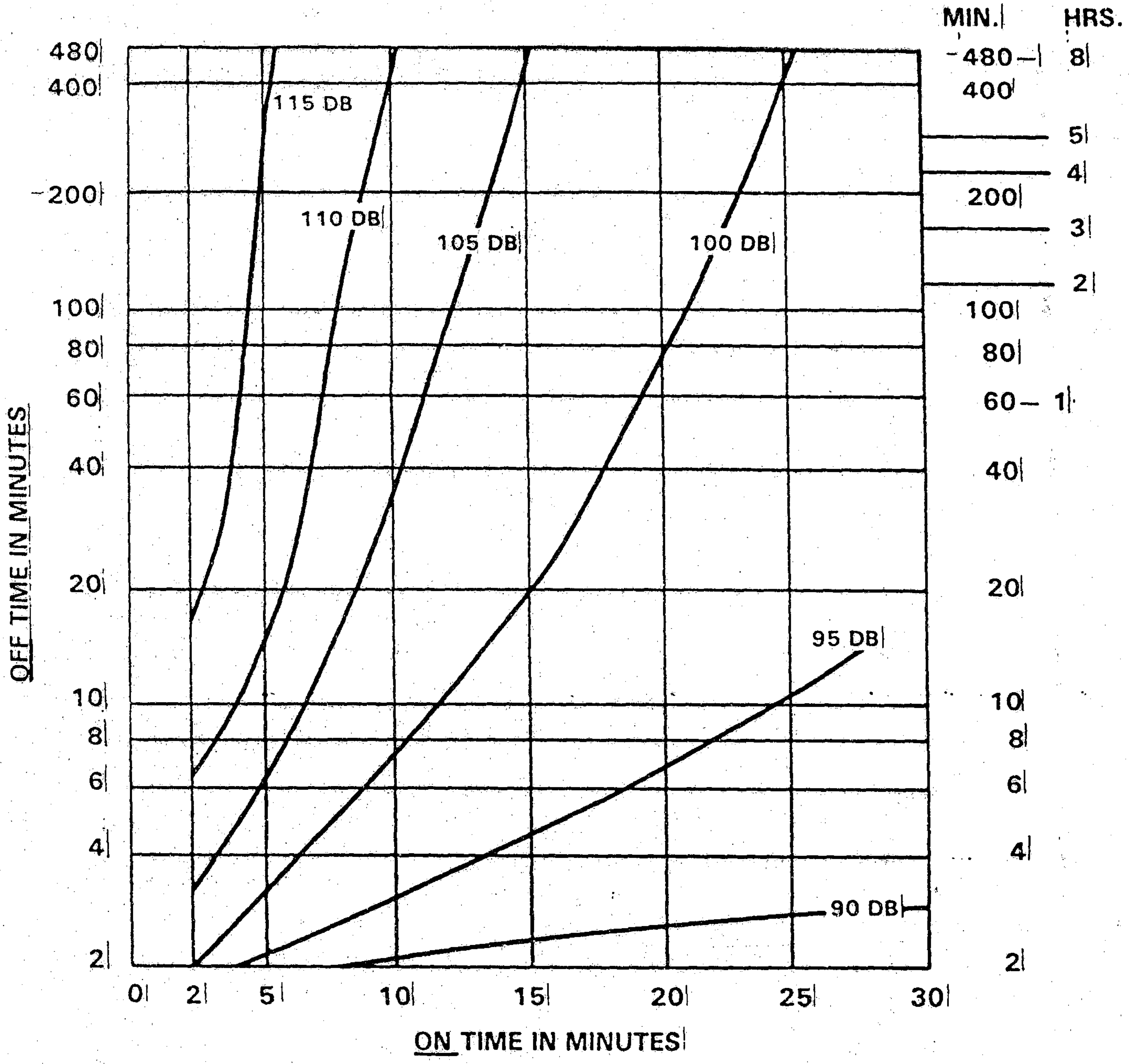

Fig. 4. Allowable exposure times for non-continuous noise. Curves represent the average value for the three octave bands between 300 and 2400 Hz. From Intersociety Committee (1967), attributed to AAOO Subcommittee on Noise in Industry (1964).

This standard was promulgated early in 1969 (Dept. Labor, 1969a), but was withdrawn after a short period.

Later in that same year the Walsh-Healey noise standard that is in effect today was issued (Dept. Labor 1969b). In this version, any special criteria for intermittent or non-continuous noise had disappeared and the 5-dB exchange rate became official.

G. ISO-1971

The ISO issued its formal recommended criteria for occupational noise exposure, R1999, in 1971. The recommendation is known to be based largely on the data of Baughn (which were published later, in 1973), although no data or rationale are mentioned in the ISO publication. ISO R1999 uses the 3-dB exchange rate based on a 40-hour work week, and permits the risk of hearing impairment to be calculated for populations exposed to any combination of noise level from 80 to 120 dB(A) and durations from 10 minutes to 40 hours.

H. EPA

In 1973, the EPA issued criteria based on the combined data and methods of Baughn (1973), Burns and Robinson (1970), and Passchier-Vermeer (1968). These criteria incorporated the 3-dB rule for assessing exposure to intermittent as well as continuous and varying noise. However, the EPA acknowledged the evidence presented by Ward (1970) and others showing that the 3-dB rule makes no allowance for recovery from TTS during intermittencies.

In its subsequent "Levels Document", EPA used the 3-dB exchange rate to assess the effect of lifetime exposures to environmental noise (EPA, 1974a). EPA concluded that the level that would just fail to produce a measurable shift in hearing threshold at 4000 Hz, even if it were experienced constantly over a lifetime, was an A-weighted average L_{eq} of 70 dB. In arriving at this decision, EPA adjusted the criterion level, making it more lenient by 5 dB. Because the criterion level had been derived from occupational exposure data, EPA reasoned that adding 5 dB would account for the intermittencies typical of environmental noise exposures. Justification for this adjustment came from Kryter (1970), who maintained that noise with levels below 65 dB for 10 percent of the time were less dangerous than continuous noise at the same level. In its Levels Document, EPA plotted curves based on other recommendations for intermittency corrections, and the "equal-energy-plus-5-dB" function generally bisected the area encompassed by the other recommendations. Displayed in Fig. 5, all of these curves show the levels and durations necessary to protect the 4000-Hz audiometric frequency.

I. Air Force-1973

When the Air Force revised its hearing conservation regulation, it adopted a 4-dB exchange rate (Air Force, 1973). This rule is purportedly based on criteria developed by H.O. Parrack, which remain unpublished except for a set of curves that appear in an EPA/Air Force joint report, displayed here in Fig. 6 (Johnson, 1973). According to Johnson (1983), the Air Force followed Parrack's recommendation for the 4-dB exchange rate because it came closest to the curve that best described TTS at the important 1000-Hz frequency. Johnson (1973) concluded from the curves in Fig. 6 that no simple function best matched the TTS values, but he recommended against anything other than a linear function because the use of TTS data was not secure enough "to warrant such refinements". He pointed out that according to these data, the 3-dB rule would best protect 4000 Hz, and the 5-dB rule would be most suitable if only the mid-frequencies, 500, 1000, and 2000 Hz were to be protected.

J. ISO-1990

The most recent standards development involving the exchange rate is a revision

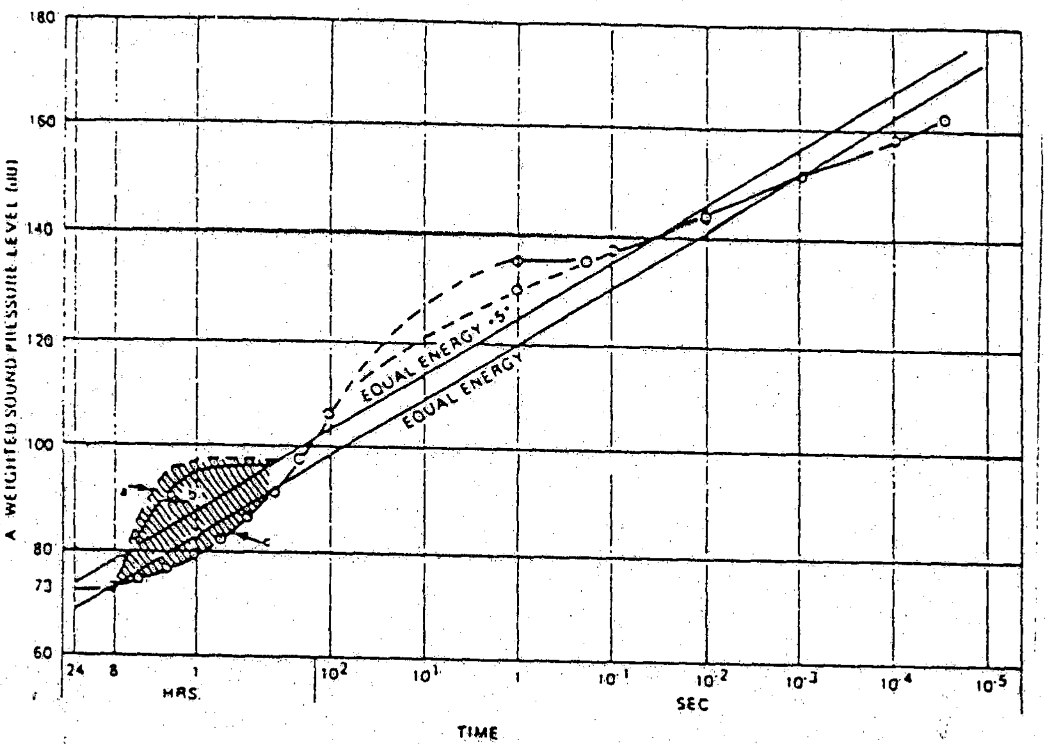

Fig. 5. Equal TTS curves for 4000 Hz as a function of exposure level and duration. Curve (a) shows the maximum intermittency correction advocated by the Intersociety Committee (1970). Curve (b) is derived from data of Ward (1973), and curve (c) represents CHABA's exchange rate for single bursts. From EPA (1974a). Note: shaded area indicates area of uncertainty.

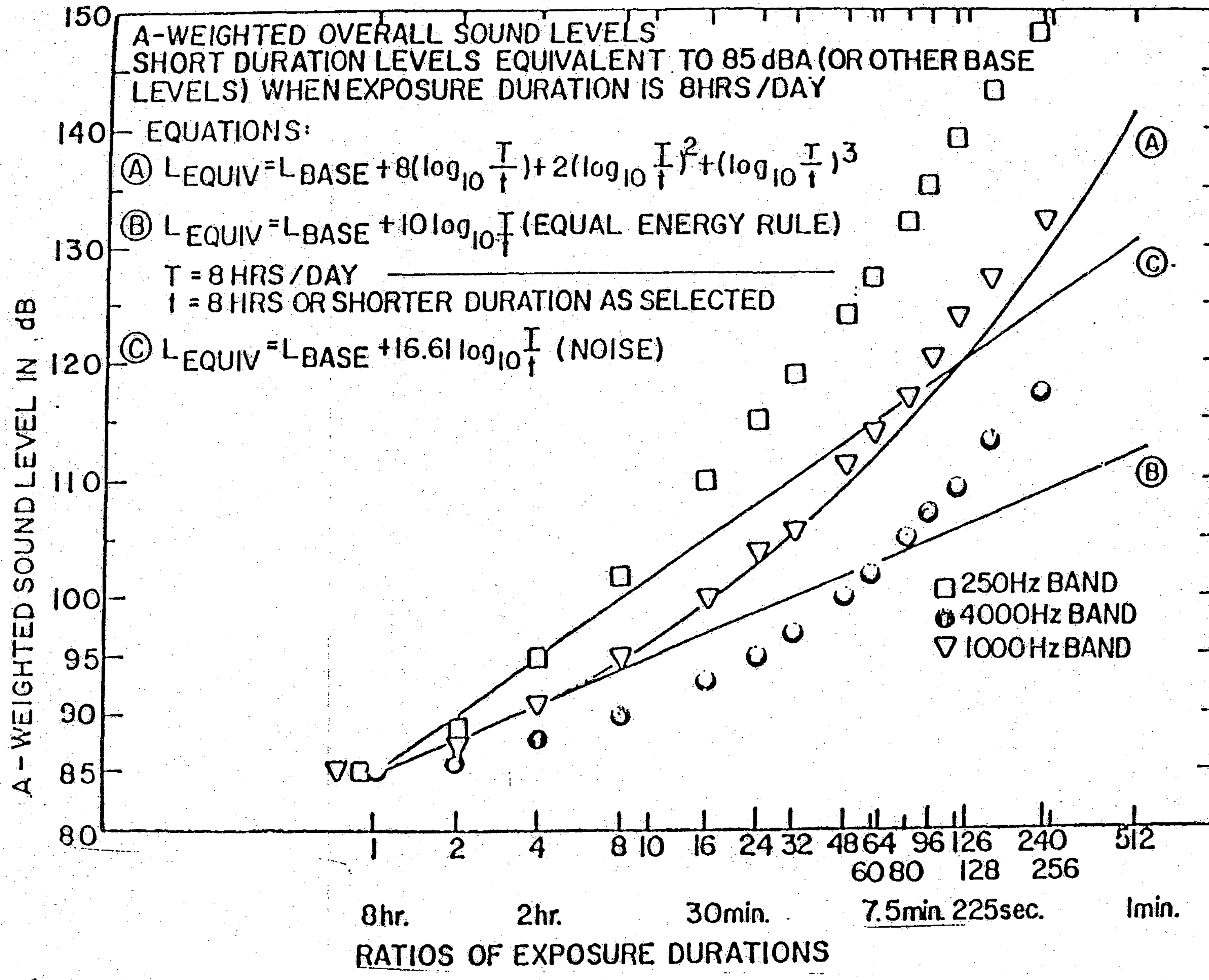

Fig. 6. Equal TTS curves for 250 Hz, 1000 Hz, and 4000 Hz as a function of exposure level and duration. Line B is the 3-dB rule's function, Line C is the 5-dB rule's function, and Line A is the curvilinear function that describes equal effect (TTS) at 1000 Hz. From Johnson (1973) attributed to Parrack (unpublished).

of the ISO standard, 1999 (1990), which applies the 3-dB rule to noise that is "steady, intermittent, fluctuating, irregular, or impulsive." The standard is to be used with sound pressure levels up to 140 dB and durations of 1 second to 24 hours. From 8-hour equivalent levels of 75 to 100 dB(A), hearing damage can be predicted for periods of less than a year to 40 years. Although the standard contains no specific justification for its predictive methods or values, references to hearing loss data from Baughn (1973), Passchier-Vermeer (1968 and 1977), and Burns and Robinson (1970) are included in the bibliography.

III. DISCUSSION OF CRITERIA AND STANDARDS

Because so many versions of the exchange rate were published between 1960 and 1970 and because so many of them were quite similar, the exact origins of the 5-dB rule are somewhat obscure. The earlier standards, the ISO proposal (1961) and the CHABA criteria (Kryter et al., 1966) specified different approaches to the assessment of continuous and non-continuous exposures. In particular, the CHABA criteria reflected a thorough attempt to predict the hazard from nearly every conceivable noise exposure pattern, based on TTS experimentation. With the drive for simplicity, however, certain parameters were omitted. Botsford (1967) combined everything into one graph, but he had to make the assumption that exposure cycles would be uniformly distributed. The Intersociety Committee (1967) simplified the intermittency graph originally developed by Glorig et al. (1961), retaining the off-time criteria but dropping the criteria for numbers of cycles. The Committee then simplified its own simplification by recommending the 5-dB rule as a close approximation of the earlier intermittency contours (1970). The proposed Walsh-Healey noise standard (Dept. Labor, 1968) again separated continuous and non-continuous noise, but made no mention of permitted exposure cycles or off-times. The 5-dB exchange rate appears to have been the natural outgrowth of the many simplifying processes that preceded it. But by this time the complex relationships between noise level and duration had traveled far from their use in the original ISO and CHABA criteria, and several additional assumptions were needed before the simplified methods could be employed.

The 5-dB exchange rate has had its detractors. For example, The EPA, has characterized OSHA's use of the 5-dB rule as a distortion of the CHABA criteria (EPA, 1974b). Whereas the CHABA criteria require evenly spaced interruptions of specific duration, the 5-dB rule allows all of the dose to be concentrated in single exposures. EPA pointed out that the validity of a scheme such as CHABA's depends upon evenly distributed exposure cycles with intervals that are both sufficiently long and quiet to permit recovery from TTS. Although the EPA had used a 5-dB *adjustment* for intermittency (as opposed to a 5-dB exchange rate), it did not recommend such an adjustment to OSHA because long periods of relative quiet may be characteristic of environmental noise, but they are not common to industrial noise.

The equal energy rule has also been criticized, mainly because of its failure to take ameliorative interruptions into account. Ward (1976) has pointed out that intermittent noise will often fail to produce as much TTS as continuous noise of the same total energy. While there is some "savings" (reduction in TTS due to intermittency) with high-frequency noise, the effect is even greater with low-frequency noise. Increasing the duration of the noise burst decreases the amount of savings over the exposure from continuous noise. He found, however, that even the 5-dB rule underestimates the savings brought about by intermittency when the noise bursts are short. But as a practical matter, Ward could see no simple way to correct the 3-dB rule for intermittency because such a correction would depend upon the on-fraction and burst duration of the noise.

To evaluate the various exchange rates critically, it would be useful to examine their underlying assumptions, most of which employ TTS_2 as the criterion of potential damage.

A. TTS_2 as a Valid Predictor of NIPTS

All of the early criteria that relied upon TTS made at least one critical assumption: that the NIPTS produced after many years of daily exposure to a given noise is about the same as the TTS measured 2 minutes after cessation of an 8-hour exposure to the same noise. It appears that this assumption has not been validated (Shaw, 1985; Ward, 1980). Burns and Robinson (1970) found a weak positive correlation between the magnitude of mid-frequency TTS and high-frequency PTS in the same workers, but nothing more promising has been reported since then. Thus, the degree to which TTS_2 is a valid predictor of long-term PTS is still not known.

B. Equal Temporary Effect Theory

The equal temporary effect theory postulates that all exposures producing a given TTS_2 are equally hazardous. Ward (1970) studied CHABA's assumption that TTS recovery is independent of the manner in which the TTS is produced, one of the conditions of the equal temporary effect theory. Normal-hearing young adults were exposed to CHABA-permissible levels and durations of short-burst intermittent, long-burst intermittent, and continuous noise. Of particular concern to Ward was the finding that some of these subjects showed delayed recovery patterns, even though their TTSs were within the expected limits. He concluded that none of CHABA's long-burst curves was conservative enough because the pattern of recovery did not reflect the assumptions CHABA had relied on. Significantly, he found that high-frequency intermittent exposures, producing the same amount of TTS as continuous noise, always required longer recoveries.

Delayed recovery from TTS was originally thought to occur only from high values of TTS, such as 40 to 50 dB (Ward 1960). However, more recent research has shown that delayed recovery can occur from moderate levels of noise if the exposures are of relatively long duration (Mills et al., 1970; Melnick, 1974; Melnick and

Maves, 1974), and from exposure to impulse noise (Luz and Hodge, 1971), as well as to high-level intermittent noise, as Ward (1970) has shown. The practical consequence of delayed recovery is that TTS may not be allowed to recover completely before the next exposure, compounding the risk of developing permanent hearing loss.

C. On-Fraction Rule

According to the "on-fraction" rule, the TTS resulting from a noise that is on 50 percent of the time is about one-half the value of a TTS resulting from a continuous exposure at the same sound pressure level (Ward, 1970). Ahaus and Ward (1975) found this rule to be valid for burst durations from 100 msec. up to 2 minutes and for on-fractions above 0.1, but the rule broke down for shorter or longer noise bursts. Hetu (1982) found that the length of the exposure cycle (on-time plus off-time) can also influence the TTS recovery period. For example, short cycles of 10 seconds can produce delayed recovery.

D. Effective Quiet (EQ)

Another important assumption is the definition of effective quiet (EQ), the sound level that will not produce TTS or impede its recovery. According to CHABA's definition of EQ, which is any level below the 8-hour criterion level for a particular band or pure tone, the level could vary from about 84 to 97 dB, depending on frequency (Kryter et al., 1966). This assumption, however, reflects an inconsistency in the criteria because the curves were based on recovery patterns that were actually obtained in the quiet of the laboratory, which is likely to be considerably below 84 dB.

The subject of EQ has generated considerable research, much of which is summarized in Table II. Research by Schmidek et al. (1972)[2] and a review of the available TTS and PTS data by Kryter (1970) prompted NIOSH to recommend an EQ level of 65 dB in its 1972 Criteria Document (NIOSH, 1972). The 65-dB level appears to be corroborated by more recent evidence. Mills (1982) has constructed a graphical representation of the risk of noise-induced hearing loss that includes data points for EQ from a number of pertinent studies. Shown in Fig. 7, the graph displays a band about 10-dB wide where there is a risk of hearing loss from long exposures and where delayed recovery also can occur. The data points at the lower edge of the band indicate EQ levels of 64-65 dB for 2000 and 4000 Hz, and about 70 dB for 500 and 1000 Hz.

It can be concluded from this discussion that certain important assumptions on which the early criteria were based have failed to be validated and others have proved to be faulty. TTS_2 is not a proven predictor of long-term PTS, the equal temporary effect theory is confounded by delayed recovery, the on-fraction rule appears to be valid only for burst durations that are not too short or too long, and the levels of EQ assumed in the CHABA criteria and the 1969 OSHA standard are insufficiently low to permit complete recovery from TTS. Moreover, as EPA (1974b) has pointed out, the amounts of NIPTS allowed by the CHABA criteria can be considered excessive; for example, as much as 45 dB at 2000 Hz and 60 dB at 3000 Hz in the most sensitive 10th percentile.

Any criterion that requires evenly spaced quiet periods of specific duration and level is probably unrealistic. Hetu (1982) points out that actual intermittencies in industry are short compared to length of exposure, and rest periods are usually infrequent and characterized by sound levels well above 65 or even 75 dB. Most industrial exposures, therefore, consist of varying, rather

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[2] In a later experiment, Schmidek and his coworkers (1975) hypothesized that during higher-level intervals, such as 77 dB(A), the protective action of the middle ear muscles decays or "adapts out" due to the lack of respite, whereas lower levels of EQ permit the muscles to relax and to allow the acoustic reflex to be fully re-triggered by the next noise burst.

Table II. Results of Research on Effective Quiet (EQ)

Source	Noise Exposure Level	EQ Level	Results
Lenhardt and Bucking (1968)*		70 dB SPL 80 dB SPL	No effect on recovery. TTS began to grow after 15 min of exposure.
Schwetz <u>et al</u>. (1970)*		75 dB SPL	Retarded TTS recovery at 1k, 2k, 3k, and 4k Hz.
Klosterkotter (1971)*		70 dB(A) 35 dB(A)	Recovery slower at 70 dB(A).
Schmidek <u>et al</u>. (1972)	Permissible levels of interrupted coal mine noise	77 dB(A) 40 dB(A)	No significant differences in TTS recovery for 4 out of 6 noise exposure conditions.
Schmidek <u>et al</u>. (1975)	3 15-min bursts of 103 dB(A) interspersed with 2 5-min interruptions	77 dB(A) 67 dB(A) 57 dB(A)	57 dB(A) group incurred significantly less TTS than other 2 groups.
Ward <u>et al</u>. (1976)	Octave bands of noise @ 90, 100, and 105 dB	Variable	High-frequency noise exposures need lower levels of EQ. Concludes 75 dB(A) adequate for industry.
Saunders <u>et al</u>. (1977)	4-kHz octave bands of noise @ 57, 65, 72, 80, 86, and 92 dB	(same as exposure levels) 57 dB (?)	Progressively longer recovery time needed for each higher level. Small amount of TTS even from 57 dB band.
Hetu (1982)		50 dB(A) 60 dB(A) 70 dB(A) 80 dB(A)	Recovery curves overlap until 60-120 min post exposure, after which the 50 dB(A) level produces most efficient recovery.
Mills (1982)		Variable (See Fig.6)	EQ for higher frequencies about 64-65 dB. EQ for lower frequencies about 70 dB.

* Cited by Passchier-Vermeer (1973)
** According to Dept. Interior proposal (1970)

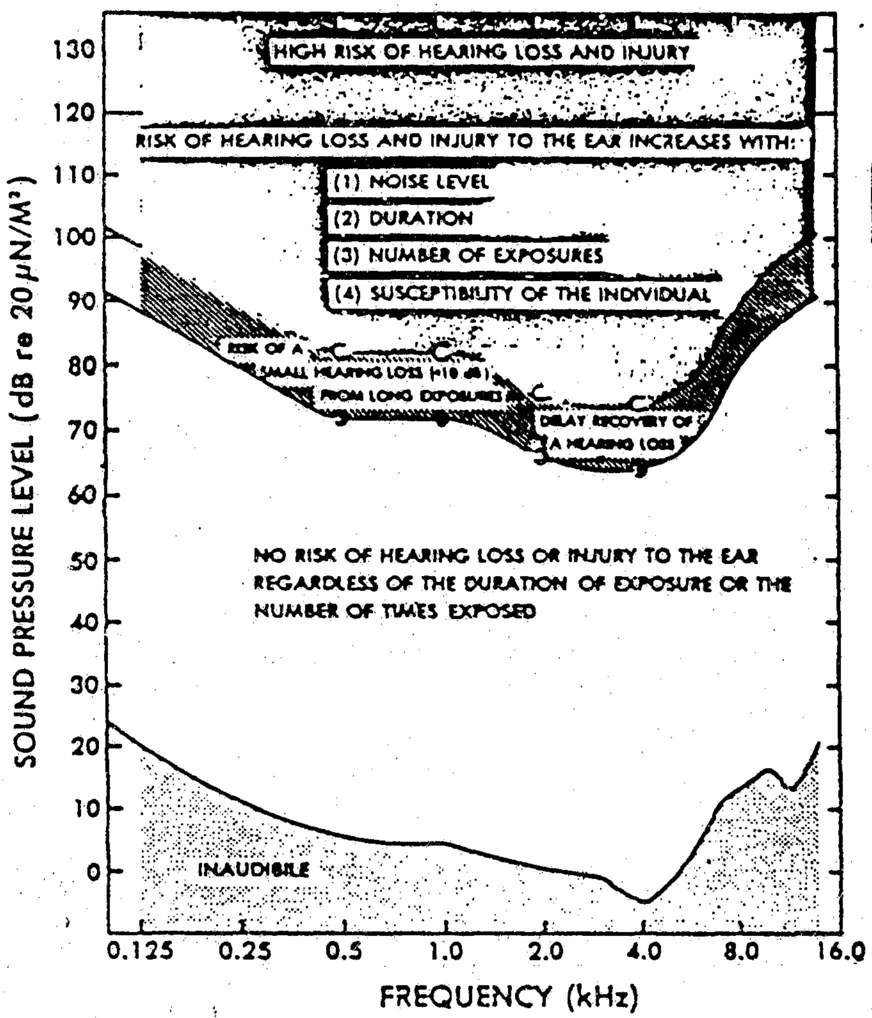

Fig. 7. Most of the range of human audibility categorized with respect to the risk of injury and hearing loss. From Mills (1982).

than intermittent noise. For instance, in a study of the effects of noise on paperworkers, NIOSH (1983) had planned to use the data gathered in this workplace as an example of intermittent noise exposure. However, the investigators found patterns of noise that "varied daily for the same worker and also varied across workers on the same day with the same job in random fashion". Undoubtedly, some recovery from TTS does take place during intervals of exposure at lower levels, even though the conditions do not meet the assumptions described above. Whether enough recovery occurs to justify a 5-dB exchange rate, however, is unlikely.

IV. LABORATORY STUDIES

A. The Relationship Among Measures of Hearing Damage

Nowadays, asymptotic threshold shift (ATS) is widely used as a predictor of permanent hearing damage. TTS from a particular noise exposure usually increases with duration of exposure until it reaches an asymptote, which is maintained until the exposure ceases. ATS is thought to represent the "upper bound" of hearing damage that can result from a particular noise exposure. Bohne and Clark (1982) found that ATS in chinchillas remained constant for a period as long as 108 days. Not surprisingly, they also found that PTS increased as the exposure continued, and after 108 days PTS was within 10 dB of ATS. An experiment by Nielsen (1982), showed that squirrel monkeys exhibited ATS for moderate noise levels (89 dB or less), but at higher levels (95 and 101 dB) TTS continued to grow for the duration of exposure. Nielsen ~~postulated~~ that humans might also continue to develop TTS (after a temporary plateau) as duration increases for periods as long as 96 hours[3]. These experiments on humans would, of course, be hazardous to perform because of the likelihood of inducing PTS. Thus, the use

[3] Nielson compared his TTS data for squirrel monkeys with the human data of several other investigators for 24-hour exposure periods. He found that although the TTS growth patterns were comparable, the monkeys demonstrated slightly less TTS than humans for a given exposure. Nielson explained this difference by the fact that the squirrel monkey's normal auditory thresholds are about 10-20 dB less sensitive than those of humans in the 125 Hz to 8000 Hz range.

of ATS as a valid predictor of the upper bound of hearing damage may be questionable.

Neither is PTS the most sensitive or reliable indicator of noise damage in all cases. Numerous studies have found that the correlation between PTS and cell damage, particularly outer hair cell (OHC) damage, is not always good. In a recent review, Clark and Bohne (1986) cite 10 studies in which threshold shift occurs without any corresponding cell loss, or encompass a broader range of frequencies than would be expected from the anatomical evidence. They also cite 5 studies showing large losses of hair cells without significant shifts in corresponding pure-tone thresholds, and they have observed OHC losses of up to 50% in the cochlear apex without showing threshold shifts for the corresponding low-frequency tones. They point out that only occasionally do the two measures agree quite well.

Clark and Bohne (1978) maintain that some of the discrepancy between behavioral audiometric results and cochlear damage may be due to the pronounced difference in the pattern of noise-induced damage between different areas of the cochlea. For example, in the cochlear apex, damage generally consists of scattered loss of OHCs only. Inner hair cells (IHCs) and supporting cells appear to be resistant until OHC losses exceed 30-50 percent. By contrast, in the base, noise-induced lesions are initially quite narrow and usually involve extensive loss of OHCs, IHCs, and supporting cells. With longer histories of exposure to low-frequency or broad-band noise, damage grows more rapidly in the base than the apex (Clark and Bohne, 1978; Bohne and Clark, 1982). These results in chinchillas are similar to the findings in noise-damaged human ears (Bredberg, 1968; Johnson and Hawkins, 1976), indicating that the relation between hair cell loss and PTS is quite different for the apex and base and that no simple equation can be derived to describe this relationship.

Thus, any of these measures of hearing damage should be employed with some degree of caution, knowing that they may not describe the true extent of damage. Loss of cochlear cells may portend hearing losses measurable by audiometry at a later date. As Ward (1980) has hypothesized, "... as they fall one by one, the cushion between normal hearing and a shift in threshold is being eroded away ...."

Some researchers nowadays are using more complex, suprathreshold listening tasks in addition to hair cell loss to assess the impact of cochlear damage. Such measures as neural and psychoacoustical tuning curves and frequency modulation detection have proved to be more sensitive than pure-tone thresholds in some cases (Clark and Bohne, 1986; Lonsbury-Martin et al., 1987). According to Lonsbury-Martin et al. (1987), each moderate exposure may result in a small amount of cellular damage that can accumulate over time until it eventually produces permanent alterations in hair-cell function. At this time, however, these measures have not been widely used to investigate issues surrounding the exchange rate.

B. Cochlear Evidence and the Exchange Rate

A number of laboratory studies concerning the relationship between noise level and duration have been conducted over the past decade and are summarized in Table III. When viewed as a whole, these studies show a pattern. Ward and his colleagues (Ward and Nelson, 1971; Ward and Turner, 1982; Ward et al., 1983) have provided evidence that the 3-dB rule applies to single exposures of various levels and duration within an 8-hour day. The data of Bohne and Pearse (1982), Bohne et al. (1985 and 1987), and Ward et al. (1982) indicate that the *total* energy hypothesis has its limits, at least for the apical region of the cochlea, although single uninterrupted exposures as long as 9 and 15 days are not typical of industrial exposures. The cochlear damage data of Ward and Turner (1982) also show some benefit from intermittency, but evidently not as much as TTS or PTS data would predict. Bohne and Pearse (1982) have also shown that protection of

Table III. Laboratory experiments bearing on the issue of the exchange rate.

Source	Stimulus	Schedule	Dependent Variable	Results
Ward and Nelson (1971)	700-2800 Hz band	4 hrs @ 114 dB 2 hrs @ 117 dB 1 hr @ 120 dB 1/2 hr @ 123 dB	PTS	High-frequency PTS was roughly equivalent for all conditions.
Saunders *et al*. (1977)	4000 Hz octave band	6 hrs on 18 hrs off for 9 days. Levels: 57, 65, 72, 80, 86, 92 dB SPL Control: 54 hrs continuous noise (Mills, 1973)	TTS, ATS	Less ATS for repeated exposures than for continuous exposure. Exposure separated by 18-hr recovery periods can tolerate a 5-dB higher level for the same ATS. Differences explained by "equivalent power" hypothesis.
Ward and Turner (1982)	700-2800 Hz band	200 minutes at 105, 108, 111, and 114 dB	Missing hair cells	Number of missing OHCs proportional to growth of sound energy.[1]
Ward and Turner (1982)	700-2800 Hz band	30-sec bursts on 0.5 time for 440 min, 30-sec bursts on 0.1 time for 2200 min, and 10-min bursts on 0.002 time for 11 weeks Control: continuous noise with same L_{eq}	Missing hair cells	Some reduction of cell loss with increased intermittency. On-fraction of 0.5 produced a 2-dB savings, extreme intermittency (0.002) resulted in a savings of 6-7 dB over continuous noise exposure.
Bohne and Pearse (1982)	500-Hz octave band	6 hrs/day for 36 days @ 95 or 9 days @ 101 dB Control: 9 days @ 95 dB	Missing hair cells	Interrupted exposures - less loss in apex but as much or greater loss in base of cochlea when compared to continuous exposures.

[1] Addition of data points from the work of Lipscomb *et al*. (1977) and Dolan *et al*. (1976) further supported the equal energy growth function.

Ward et al. (1982)	700-2800 Hz band	9 work weeks (8 hr/day, M-F) @ 92 dB Control: 15 days continuous noise @ 92 dB	PTS and missing hair cells	Improvement in both PTS and cochlear damage from 16-hour interruptions.
Ward et al. (1983)	700-2800 Hz band	48 min/day, M-F, 9 wks @102 dB Control: 9 work weeks @ 92 dB	Missing hair cells	Total missing OHC was nearly same for the two exposures.[2]
Bohne et al. (1985)	500-Hz octave band	1. 6 hrs/day, 36 days @ 95 (18-hr rest) 2. 6 hrs/day, 9 days @ 101 (18-hr rest) 3. 6 hrs/every 2 days, 72 days @ 95 (42 hr-rest) 4. 6 hrs/week, 36 weeks @ 95 dB (162-hr rest) Control: 9 days @ 95 dB	Missing hair cells	General pattern of damage same: scattered loss in apex, severely damaged narrow areas in base (HFLs)[3], but less damage for interrupted exposures. All interrupted exposures produced less damage in apex. Groups 1 & 2 showed as much loss in base as continuous exposure. Groups 3 & 4 showed less damage in both base and apex.
Lonsbury-Martin et al.[4] (1987)	100-dB pure tones with frequencies ranging from 354 Hz to 16 kHz in half-octave steps	One exposure/day. One monkey, 6 mo., total 5.5 hrs. Two monkeys - 18 mo., total 13.4 hrs and 14.4 hrs.	PTS, thresholds from cochlear nucleus, missing hair cells and neural damage.	6-mo. monkey no PTS at any frequency, neural thresholds elevated. 18-mo. monkeys some high-frequency PTS, neural thresholds elevated. HFLs in absence of behavioral loss in short-term exposure.

[2] Authors concluded that the "total-energy" hypothesis did not hold (see results of Ward et al., 1982), but that the "equal-energy" theory held, at least for single daily exposures.

[3] HFL = "high-frequency lesion"

[4] Subjects used in this experiment were 3 rhesus monkeys.

Bohne et al. (1987)	4-kHz octave band	1. 6 hrs/day, 36 days @ 80 dB (18-hr rest) 2. 6 hrs/2 days, 72 days @ 80 dB (42-hr rest) 3. 6 hrs/week, 36 weeks @ 80 dB (162-hr rest) 4. 6 hrs/day, 36 days @ 86 dB (18 hr-rest) Control: 9 days @ 80 dB[5]	Missing hair cells in cochlear base	Interrupted exposures produced same pattern of cell loss as continuous, but incidence and size of lesions were less. Recovery time course different for high-frequency noise: 18 hours sufficient to protect cochlear base against 4 kHz at these levels, (but not against 500 Hz, as above).
Clark et al. (1987)	500-Hz octave band	1. 6 hrs/day, 36 days @ 95 dB 2. 15 min/hr, 144 days @ 95 dB Control:9 days @ 95 dB	TS_{1hr}, TS_{18hr}, PTS, missing hair cells	ATS not found.[6] TS_{1hr} declined to near baseline levels, especially in 15-min group. 6-hr group showed slightly less PTS and cell loss than continuous 9-day exposure. 15-min group showed no PTS and much less cochlear damage than continuous noise exposure.
Sinex et al. (1987)	500-Hz octave band	15 min/hr, 144 days at 95 dB Hearing parameters measured after 4 and 40 days.	Action potentials (AP), neural tuning curves, missing hair cells.	APs and tuning curves showed same recovery pattern and magnitude as observed with behavioral tests. Also, extent of OHC loss often greater after 40 days than 4 days even though APs lower.

5 Exposures of groups 1-3 and controls are of equivalent energy.

6 This finding was not in agreement to the ATS finding of Saunders et al. (1977), so Clark et al. (1987) concluded that the equivalent power hypothesis was not justified.

the cochlear base may require the 3-dB rule even when intermittent exposures are spread out over long periods.

Aside from Ward and Turner (1982), only two of these experiments have used intermittent noise with on-times shorter than 6 hours. Clark et al. (1987) exposed one of their subject groups to noise for 15 minutes per hour, and this group showed significantly less PTS and cochlear damage than the group exposed to equivalent sound energy for 6 hours per day. This experiment was then replicated by Sinex et al. (1987) using cochlear nucleus action potentials and neural tuning curves, which confirmed the behavioral results of the earlier study.

Most of the intermittent exposures used in the studies described in Table III are more conducive to recovery from TTS than would be exposures in typical industrial environments. Noise bursts and interruptions in the laboratory are evenly spaced and quiet levels are generally below 65 or 70 dB. Moreover, the exposure cycles are often esoteric; for example, 1 hour on and 1 hour off for 15 hours, or 10-minute bursts twice a week. While some of these experiments do show definite benefits from intermittencies, the extent to which these benefits would be realized in actual industrial conditions is open to question.

IV. FIELD STUDIES

Nearly all of the field studies of noise exposure and hearing loss have some weakness, however small in some cases, even the most rigorously designed and executed ones. Examples of these weaknesses would be small sample sizes in certain subgroups, sporadic wearing of hearing protection, and the omission of noise measurement data and other details of experimental design. Despite their shortcomings field studies are extremely useful, especially when taken as a group, where trends become apparent. They are the only mechanism for studying human NIPTS in real-world conditions. Unfortunately, new retrospective studies would be of questionable value because they would be influenced to a varying and unknown extent by the use of hearing protectors. However, several studies have been carried out prior to the wide scale implementation of hearing protector programs.

A. Studies of Continuous and Varying noise

One of the most well known studies to investigate the exchange rate is that of Burns and Robinson (1970). The authors describe the noise exposures used in their study as "reasonably steady"[4] and not markedly impulsive in character. Measurements were made with a B&K sound level meter set to "fast" response, and the results were analyzed statistically in terms of the sound level exceeded for a given percentage of the daily exposure level. Burns and Robinson report that some of their subjects moved around quite a bit and were exposed to a wide variety of noise levels, while others were exposed to uniform levels throughout the day. The majority of the cases were in between, "necessitating sampling on a space and time basis." The difference between the median noise level and the L_2 (the level exceeded for 2 percent of the day) varied from 0 up to 15 dB, but was generally 5 dB or less. These noise environments would best be described as continuous or varying.

Potential subjects were thoroughly pre-screened, excluding those who had been exposed to gunfire or who had a history of ear disease or abnormality. Also excluded were subjects with language difficulties and those whose exposure histories were not readily quantifiable. As a result of the pre-selection process only a "relatively small proportion" of the original volunteers remained in the sample (Burns and Robinson, 1970). Then an additional 11% of the pre-selected population was excluded on the basis of an otological examination. The actual study population consisted of 759 subjects whose exposure durations ranged

[4] The term "reasonably steady" presumably includes non-continuous as well as continuous noise, as they are defined in this report.

from one month to 50 years and the range of A-weighted average noise levels was from 75 to 120 dB.

Subjects' age-corrected hearing levels were plotted according to their noise exposure level. The L_2 statistic appeared to be the best descriptor of hearing loss. However, the simple L_{eq} proved to be a close second. Because of its inherent simplicity and ease of use, Burns and Robinson adopted the L_{eq}, even though it would be less exact than the L_2 for strongly fluctuating noise environments. On the basis of the resulting formula, Robinson and Cook (1968) were able to predict hearing loss in various percentages of any population exposed to noise for periods of months to many years.

In a more recent field study Evans and Ming (1982) examined the effects of noise on 300 workers in Hong Kong engaged in a variety of occupations, including textile weaving and spinning, metalworking, bottling, and aircraft maintenance. Noise measurements were made with a B&K 2209 sound level meter and a B&K 4424 dosimeter set to the 3-dB exchange rate. Age-corrected hearing levels for textile spinners agreed with Robinson's predictions (in Burns and Robinson, 1970; Robinson and Shipton, 1977), but other groups showed more hearing loss than would have been predicted. Evans and Ming believe that the differences were due to the fact that the Hong Kong workers were not rigorously screened to exclude otological abnormalities. The authors cite Robinson and Shipton (1977), who suggest an adjustment of about 5 dB for a population that has not been otologically screened. After adjusting the data, Evans and Ming found that the remaining groups, with the exception of the metalworkers, fell within the predictions.

The fact that the metalworkers in the Evans and Ming study continued to show losses greater than the 3-dB rule would have predicted may have been due to the presence of impulsive noise and the inability of the B&K 4424 dosimeter (with a crest factor capability of only 10 dB) to integrate all of the impulsive energy.

The authors offer no explanation as to why the spinners needed no adjustment for otological screening while the other categories of workers did. One possible explanation could be the predominance of women workers in the Hong Kong spinning industry, whose hearing threshold levels would tend to be somewhat better than the population used by Burns and Robinson, of whom 56 percent were men.[5]

B. Intermittent Noise

Certain occupational noise exposures can be more easily classified as intermittent because they take place outdoors, without hard walls, floors, and ceilings to promote a reverberant build-up of sound, and where the ambient environment during the intermittencies can be truly quiet. Examples would be forestry and certain kinds of mining operations.

In a study of 320 Swedish forestry workers, Holmgren et al. (1971) reported average[6] exposure levels of 95.3 dB(A) for power saw operators and 97.8 dB(A) for tractor operators. Hearing levels were comparable to those reported by Kylin (1960) in ears exposed for approximately the same duration to continuous noise at 90 dB, leading the authors to conclude that the intermittent exposures were not as harmful. They did mention, however, that there had been a considerable increase in the use of the power saw in forestry over recent years, which would mean that the total exposure may have been overestimated by recent measurements. In another Swedish study, Johansson et al. (1973) also compared the hearing levels of workers exposed to intermittent noise to the continuous-noise hearing loss data of Kylin. Once again, the investigators found hearing levels comparable to those resulting from exposure to lower levels of continuous noise. Results such as these led the authors to recommend a 5-dB allowance in the

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5 Evidence that women incur less hearing loss than men from comparable noise exposures is provided by Burns and Robinson (1970), Berger et al. (1978), and Royster et al. (1980).

6 Average exposure levels were calculated in these kinds of studies according to the 3-dB rule unless specified otherwise.

permissible exposure limit for intermittent noise, meaning that the total L_{eq} could be 5 dB higher in intermittent noise conditions.[7]

In another study of forestry workers, the Institut National de Recherche et de Securite, compared the effects of intermittent exposures in woodcutters to those of the more continuous exposures in sawmill workers (INRS, 1978). Average exposure levels for the woodcutters ranged from 102 to 105 dB(A), and for sawmill workers from 91 to 99.5 dB(A). Because the hearing levels for both groups were approximately the same, the authors concluded that the continuous sawmill noise was more damaging than the intermittent exposures of the forestry workers. The authors did caution that forestry work tended to be seasonal, and that it was not uncommon to find people who worked both as farmers and as woodcutters. If this were the case, woodcutters could have fewer actual days of noisy work (assuming that farming was not equally noisy) and, consequently, less hearing loss.

Several studies of noise-induced hearing loss have been conducted on miners. Ward (1974) cites certain European studies of miners as supporting the contention that exposure to intermittent noise is less harmful than exposure to continuous noise: Blaha and Slepicka (1967); Jonsson (1967); and Motta and Tarsitani (1969). An investigation of coal miners' hearing levels by Sataloff et al. (1969) is one of the most frequently cited studies supporting the beneficial effects of intermittency. In this study, miners were exposed to drilling noise at about 105 to 122 dB(A) for durations ranging from about 3 seconds to 7 minutes, totalling around 3 hours per day. Quiet intervals ranged from 15 seconds to several hours. Sataloff et al. (1969) found that nearly all miners had high-frequency hearing losses and 23 percent of them had average hearing levels at 500, 1000, and 2000 Hz greater than 25 dB (re ANSI, 1969). However, the losses were not as great as those that would be predicted for exposure to continuous noise, or even for intermittent noise according to the CHABA criteria (Kryter et al., 1966). The

7 This recommendation is similar to the one used by EPA (1974a) in converting from the industrial to the environmental noise condition.

authors concluded that the hazard from noise interrupted about 40 times a day is approximately the same as the hazard from a continuous noise about 20 dB lower in level. The results of this study may have been influenced by the fact that 82 percent of the workers stated that they had worn hearing protectors, although the authors report that the majority of the miners had many years of exposure prior to the use of protectors. Another shortcoming is the fact that actual daily dose is not reported, either in L_{eq} or L_{OSHA}, nor are any measurement details, such as the use of fast or slow meter response.

Two studies by NIOSH failed to confirm the findings of the intermittent noise studies described above. One was a large study of hearing loss in coal miners exposed to various sources of mining noise, including continuous mining machines at 87 to 107 dB(A), drilling and bolting at 93 to 119 dB(A), loading coal at 85 to 108 dB(A), and shuttling coal and moving of mining equipment at 84 to 98 dB(A) (NIOSH, 1976). On-times ranged from a few seconds to 4 or 5 minutes, and off-times also ranged from seconds to minutes. Despite the relatively high noise levels, actual dose, when calculated according to the 5-dB rule, showed that 88 percent of the miners had doses of less than 100 percent (using a criterion level of 90 dB). These doses might have been slightly underestimated for some exposures because the analysis was made using a 90 dB(A) "cutoff", meaning that sound levels below 90 dB(A) were excluded from the calculations. The miners' hearing levels were considerably greater than those of non-noise exposed controls and greater than the levels that would have been predicted by the 5-dB rule. To test the effect of an 85 dB(A) cutoff with both the 5-dB and 3-dB exchange rates, the authors correlated the resulting doses with the miners' hearing losses. However, they found correlations so small that it was impossible to conclude which rating scheme was best[8]. They did state that the "equivalent" (L_{OSHA}) noise levels were only 85 to 90 dB, but that the miners' hearing levels were similar to those of a population exposed to continuous noise between 90 to 95 dB,

[8] Unfortunately, the authors do not give comparisons between average doses calculated according to L_{OSHA} and L_{eq}.

leading them to conclude that the results did not support the notion that intermittent coal mine noise is far less hazardous than continuous noise.

Another NIOSH investigation concerned fire fighters' noise exposures (NIOSH, 1982). A standard sound level meter and Metrologger db-301/652 dosimeters were used to assess the fire fighters' highly intermittent noise exposures. Sound levels of the fire fighting equipment ranged from about 91 to 116 dB(A), but 8-hour average exposure levels, calculated according to the 5-dB rule, were only about 63 to 85 dB(A). When hearing levels were compared to those of the U.S. National Health Survey (Dept. HEW, 1965), young fire fighters showed more acute hearing but older fire fighters showed significantly more hearing loss, particularly in the high frequencies. The NIOSH team concluded that the experienced fire fighters showed greater losses than would have been expected from the relatively mild exposure doses. (If the noise doses had been calculated according to the 3-dB rule they would have been somewhat higher.)

C. <u>Passchier-Vermeer's Analysis</u>

Probably the most comprehensive investigation of the effects of intermittent and varying noise was undertaken by Passchier-Vermeer (1973), who scrutinized more than 100 pertinent studies. She selected 11 studies for analysis of the time-varying effects, based on such factors as adequacy of noise exposure data, total exposure time of at least 10 years, and a difference of at least 25 dB between the highest and lowest exposure levels. Passchier-Vermeer also used subject screening as a basis for selecting the 11 studies, but gives few details about the screening procedures used by each investigator. In general, she selected studies where subjects showed no previous exposure to noise at other jobs and no prior ear damage or otologic abnormalities. Two of these studies reported occasional use of hearing protectors and one study included some subjects who had been exposed to gun noise. It can be assumed that the 11 studies had employed varying degrees of screening, but not to the extent of Burns and Robinson.

Subjects were divided into 20 groups according to whether their exposures were varying or intermittent (by Passchier-Vermeer's definitions given in Table I), the duration of the noise bursts, and the 8-hour equivalent exposure level. Median hearing levels for the frequencies 500, 1000, 2000, 3000, 4000, and 6000 Hz were plotted according to 8-hour equivalent levels (calculated using the 3-dB rule) and compared to the data from exposures to continuous noise from both Passchier-Vermeer (1971) and Burns and Robinson (1970).

Fig. 8 shows the relationship between the data points from the studies analyzed by Passchier-Vermeer and her predictive curve developed from continuous noise hearing loss data for the 3000-Hz audiometric frequency. The results show good general agreement between the data from exposure to varying noise (represented by circles) and Passchier-Vermeer's data for continuous noise. Good agreement is also evidenced for the intermittent data points (squares), except for the 113-dB equivalent level point attributed to Sataloff et al. (1969), which indicates less hearing loss than from the continuous noise.

For purposes of comparison, hearing loss curves for Passchier-Vermeer's continuous noise are contrasted with those of Burns and Robinson (1970) in Fig. 9. Although she offers no statistical comparisons, one can easily see that Passchier-Vermeer's curves demonstrate substantially greater losses at 3000 Hz and 4000 Hz and that the differences increase with increasing noise level. Passchier-Vermeer mentions that Burns and Robinson believe the differences to be due to subject-selection criteria, but she maintains that if that were the case the curves should be parallel, which they are not. However, she is unable to offer an alternative explanation.

In Fig. 10, Passchier-Vermeer's data from intermittent and varying noise are compared to the predictive curve for 3000 Hz from Burns and Robinson (1970). Not unexpectedly, most of the intermittent and varying noise data points fall slightly above the continuous noise curve, indicating more hearing loss for

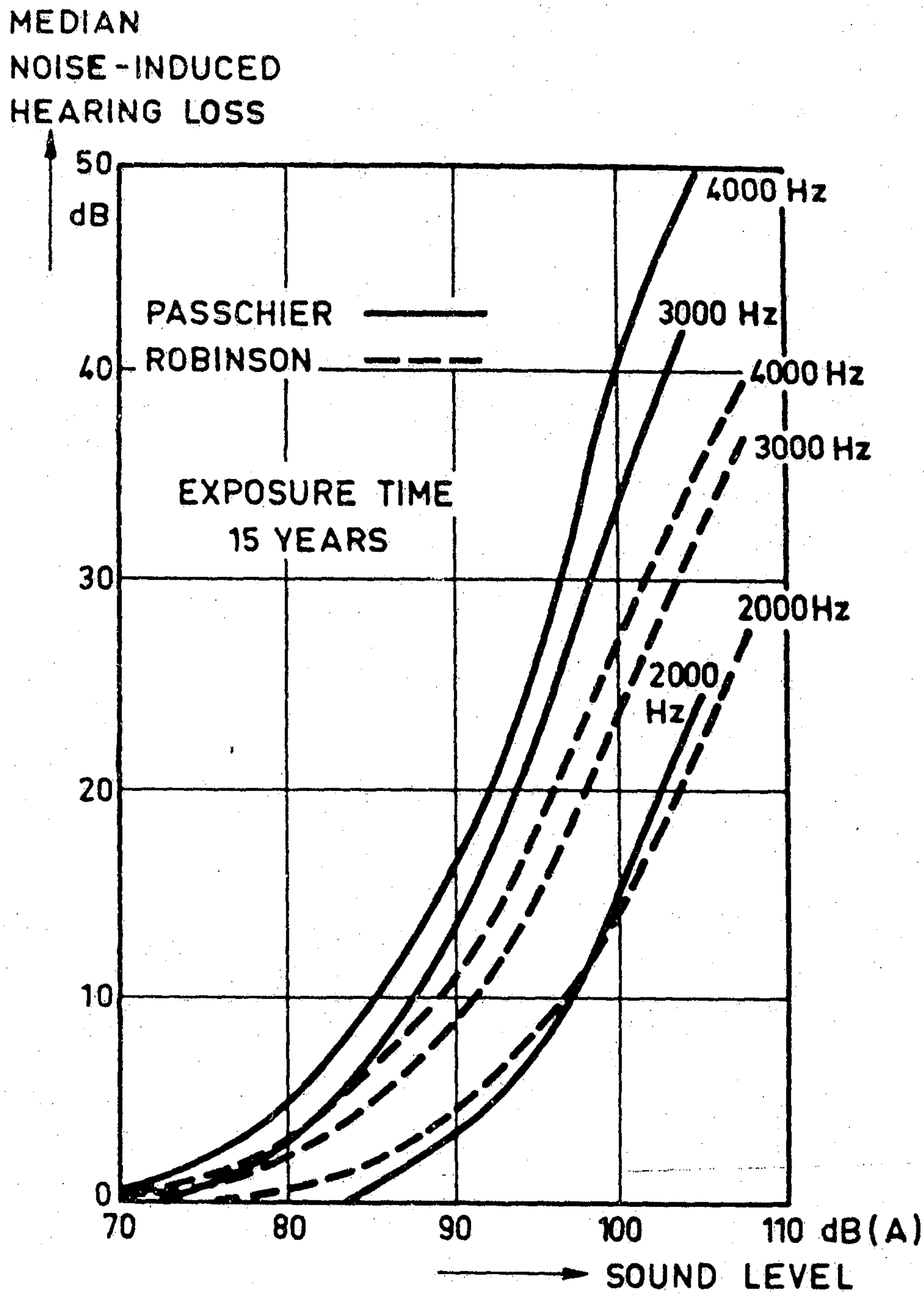

Fig. 8. Median noise-induced hearing losses at 3000 Hz from exposure to varying (circles) and intermittent (squares) noise for 15 years, as a function of equivalent A-weighted sound level. Curve represents Passchier-Vermeer's estimates for hearing loss due to 15 years' exposure to continuous noise. From Passchier-Vermeer (1973).

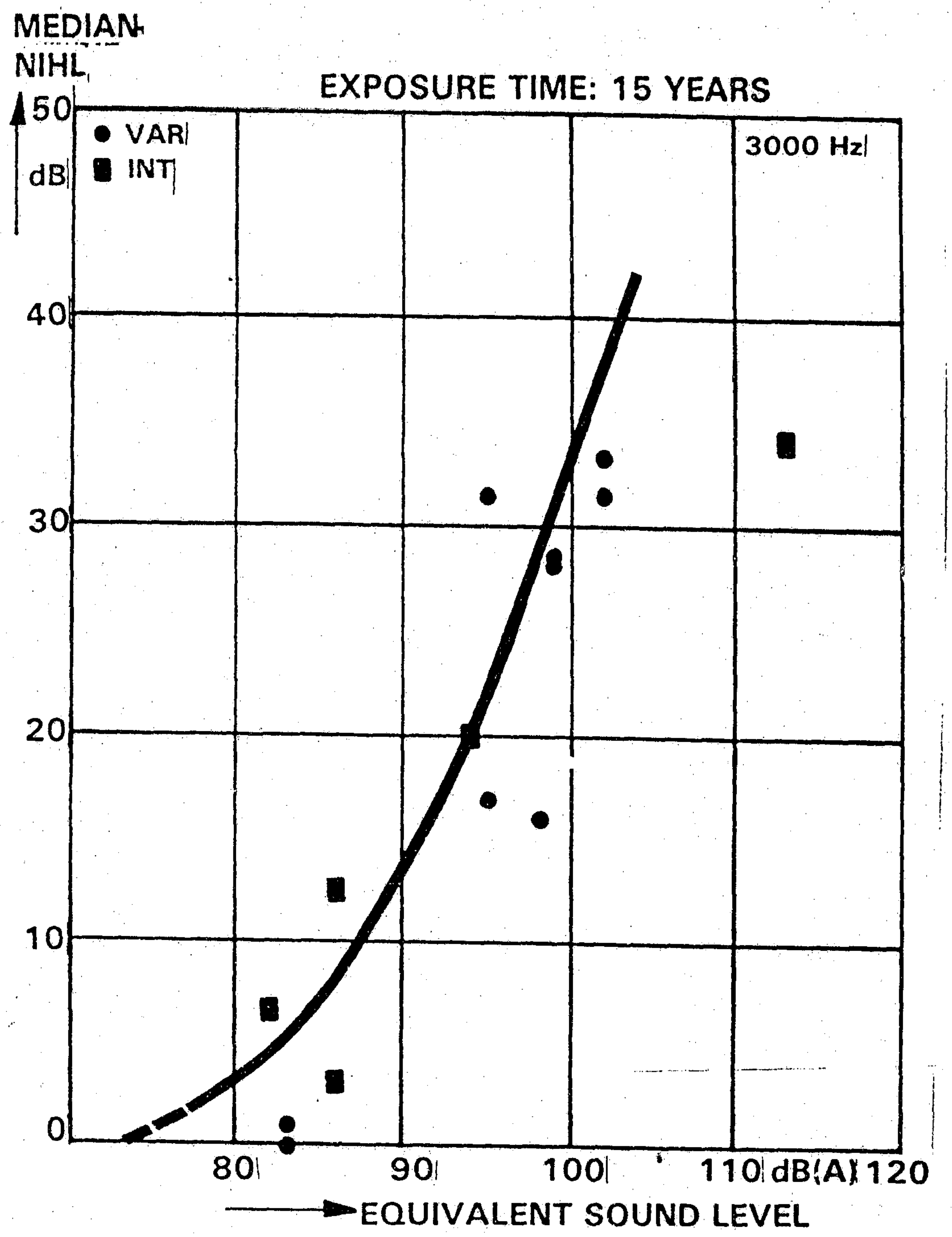

Fig. 9. NIPTS curves for Passchier-Vermeer's continuous noise data contrasted with those of Burns and Robinson (1970). From Passchier-Vermeer (1973).

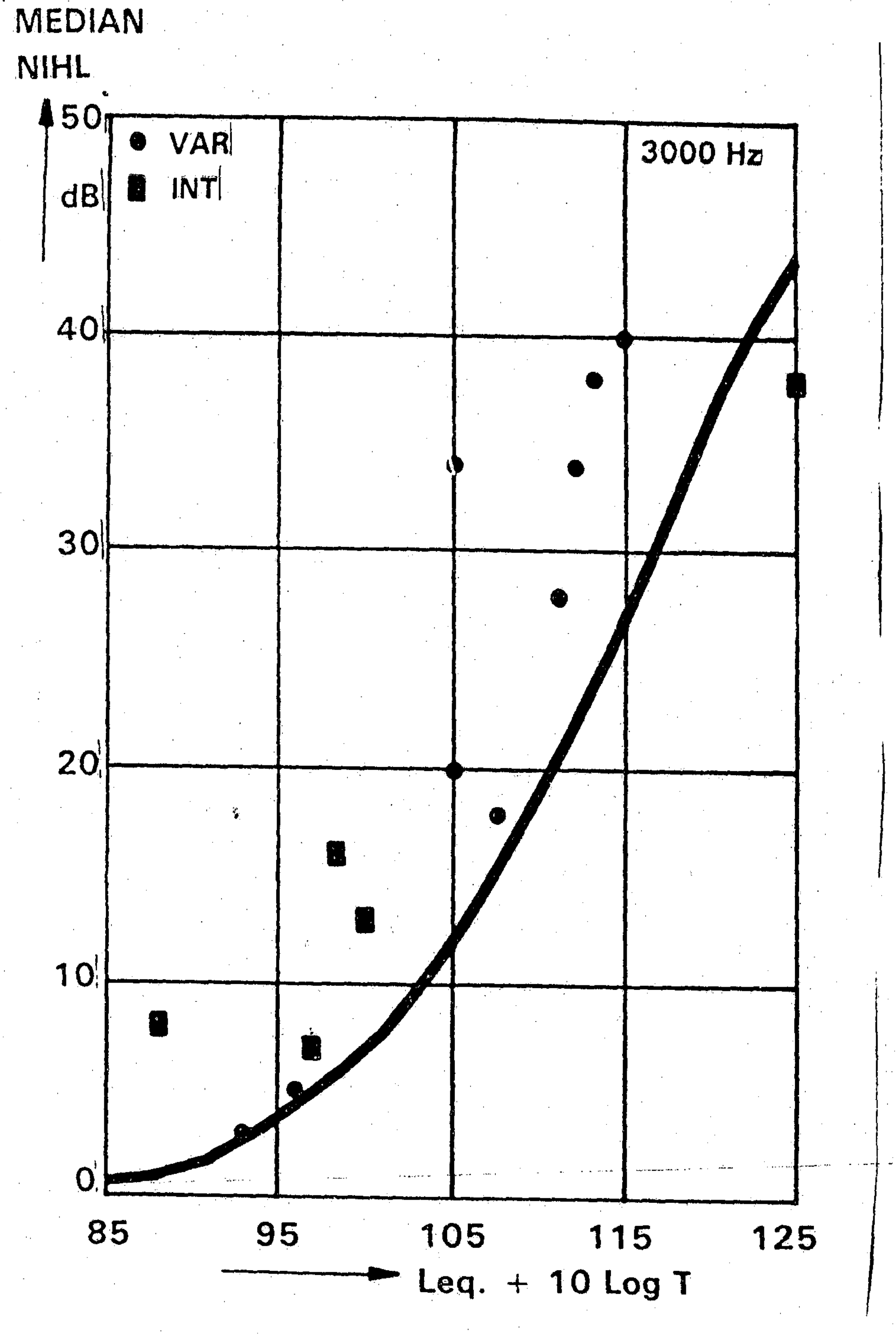

Fig. 10. Median noise-induced hearing losses at 3000 Hz from exposure to varying (circles) and intermittent (squares) noise as a function of noise "immission" level (L_{eq} + 10 log T, where T is the exposure time in years). Curve represents estimates of Burns and Robinson (1970) for hearing loss due to 15 years' exposure to continuous noise. From Passchier-Vermeer (1973).

Passchier-Vermeer's intermittent exposures than for Burns and Robinson's continuous ones. Analysis of the data for the other frequencies yielded similar results.

Passchier-Vermeer concludes from the comparisons using both her data and those of Burns and Robinson that the equal-energy rule describes hearing loss from intermittent and varying noise quite well for daily average exposures below about 100 dB. On the basis of the limited data above this level (mostly from mining), she concludes that some intermittent noise can be less harmful than continuous noise, and she postulates that any benefits of intermittency might be due to the level of effective quiet between noise bursts.

D. Shaw's Analysis

More recently, Shaw (1985) has reexamined Passchier-Vermeer's analysis using the ISO standard 1999 (1990).[9] Shaw's procedure was to "re-normalize" the data from Passchier-Vermeer's 20 varying and intermittent groups to a 15-year exposure time, assuming that the growth of median NIPTS would follow the mathematical functions incorporated in the new ISO standard. Fig. 11 shows Shaw's comparisons between the Passchier-Vermeer data for varying and intermittent noise and the ISO 15-year predictions for median noise-induced threshold shift at the frequencies 500 Hz through 6000 Hz as a function of equivalent A-weighted sound level. The ISO curve is dashed above an L_{eq} of 100 dB because the standard cautions against extrapolating to higher levels. According to the standard, such extrapolations "are not supported by quantitative data."

Once again, it is evident that the data for varying and intermittent noise agree fairly well with the predictions based on noise that is generally continuous. The only exception is the 6000-Hz frequency, where the hearing loss from varying

[9] Although the official date of ISO 1999.2 is 1990, it has been essentially unchanged since an earlier draft issued in 1982.

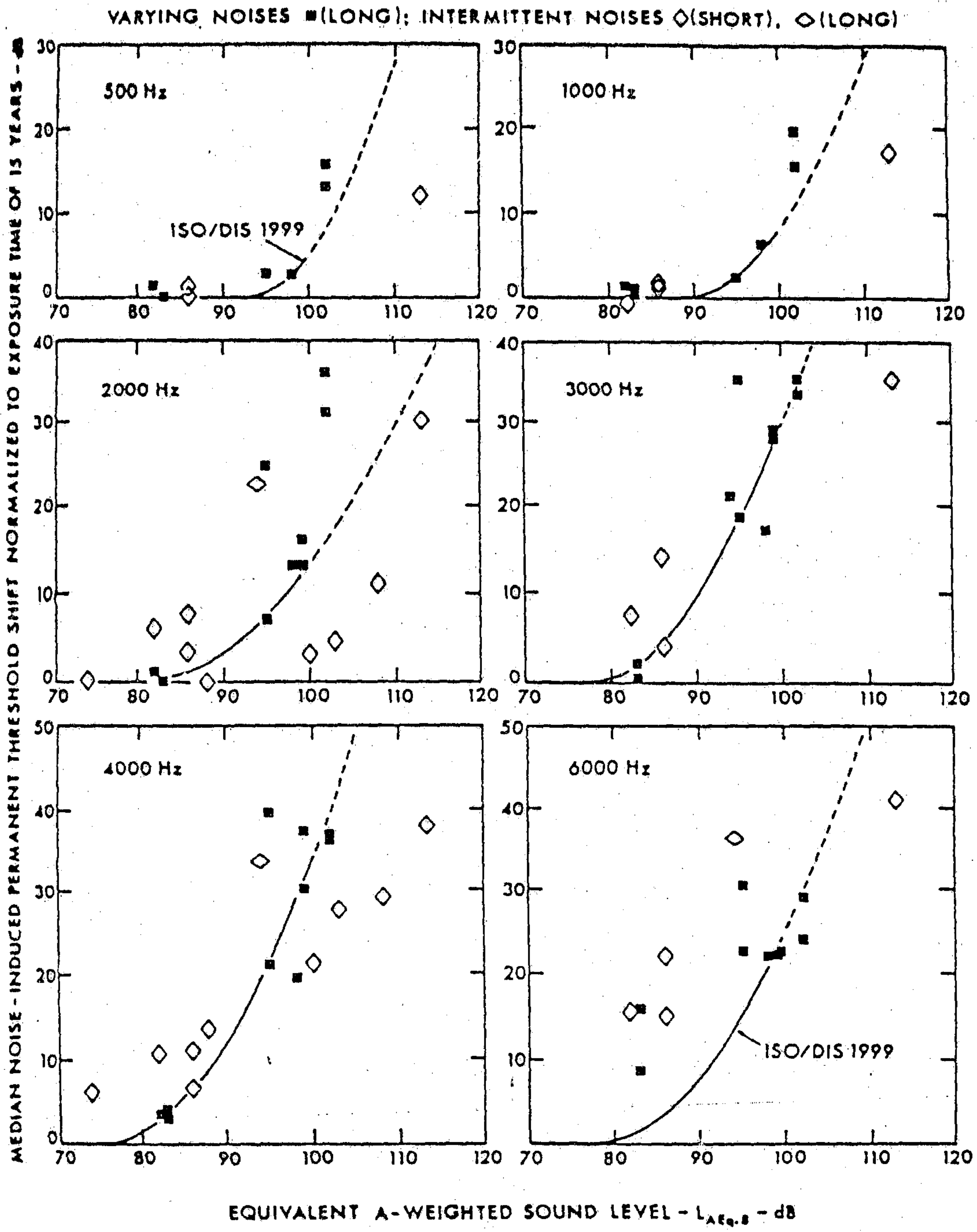

Fig. 11. Median NIPTS as a function of A-weighted sound level. Epidemiological data selected by Passchier-Vermeer for varying and intermittent noise are compared to the 15-year predictive curve generated by ISO 1999.2 The 20 Passchier-Vermeer data sets have been re-normalized to an exposure time of 15 years. From Shaw (1985).

and intermittent noise appears greater than would be predicted by the ISO standard. Shaw points out that the median NIPTS from individual studies may lie considerably above or below the ISO curve, causing differences in predicted noise levels of 5 dB or more for a given level of NIPTS. But this fact does not detract from the validity of the 3-dB rule. He summarizes as follows:

> At present it is an open question whether such deviations are really due to the approximate nature of $L_{Aeq,8h}$ as a measure of noise exposure or simply confirmation of well known imperfections in audiometric technique, the treatment of hearing data, the measurement of noise level, and the estimation of exposure duration and temporal pattern. It is, however, quite clear that Fig. 3 [Fig. 11 in this report] offers little support for the 5 dB trading relationship since there is no evidence of a <u>systematic</u> displacement of data to the <u>right</u> of the ISO median curves. As noted earlier, the only <u>systematic</u> displacement visible in Fig. 3 [Fig. 11] is at 6 kHz and this is to the <u>left</u> of the curve. Such a displacement, if taken at face value, would suggest that intermittent noises of moderate daily A-weighted energy tend to produce <u>more</u> hearing loss at 6 kHz than steady noise with the same daily energy. (Shaw, 1985, p.21)

E. Discussion of Field Studies

The studies and analyses discussed above give considerable support to the 3-dB exchange rate to assess the effects from continuous and varying noise exposures. The situation becomes more complex when noise becomes truly intermittent, i.e. when there are large differences between high and low levels, and levels in between occur rarely. The studies of forestry workers and miners indicate that the frequent periods of quiet between noise bursts can, in some circumstances, ameliorate the effects of noise exposure. The fact that all of these studies took place outdoors is not coincidental, since most indoor workplaces do not provide conditions that are quiet enough to facilitate recovery from TTS.

Some studies of intermittent noise exposure do have their weakness as explained above. For example, the study by Sataloff <u>et al</u>. (1969) states that the miners were exposed to drilling noises from 105 to 122 dB(A), but omits information about time-weighted average exposure level or noise dose. By contrast, the NIOSH

(1976) miners were also exposed to high levels of intermittent noise, ranging from 84 to 119 dB(A), and yet their 8-hour equivalent exposure levels, (calculated according to the 5-dB exchange rate), were, in most cases, less than 90 dB(A). This is not to say that the two populations were exactly comparable, but that the actual dose may be somewhat lower than it would appear at first glance.

The differences between the Swedish (Holmgren <u>et al</u>., 1971: Johansson <u>et al</u>., 1973) and French (INRS, 1978) forestry workers and their continuously exposed counterparts are more difficult to explain. The advent of the power saw may have caused recent exposure levels to be substantially higher than they were in former days. Also, the seasonal nature of forestry work may further reduce the total cumulative exposure, so that the daily equivalent levels that are given are actually higher than they would be if these factors were considered. Then again, the opportunity to recover from TTS during the quiet periods may be the key to the difference. This appears to be a trend exhibited by several (Sataloff <u>et al</u>., 1969; Holmgren <u>et al</u>., 1971; Johansson <u>et al</u>., 1973; INRS, 1978) but not all (NIOSH, 1976; NIOSH, 1982; Passchier-Vermeer, 1973) of the studies of hearing loss from outdoor intermittent noise exposures. The apparent weaknesses in these studies, as well as the lack of corroboration by the NIOSH studies or by the analyses of Passchier-Vermeer and Shaw, do not give resounding support to their conclusions that intermittent noise is less harmful to hearing than continuous noise.

The analysis by Passchier-Vermeer and the subsequent reanalysis of these data by Shaw give considerable support to the 3-dB rule in all types of non-impulsive noise environments.

V. SUMMARY AND CONCLUSIONS

Because the validity of the CHABA postulates is open to serious question and also because TTS is not a good predictor of permanent hearing damage, criteria based on TTS patterns should not be relied upon for predicting the long-term adverse effects of noise exposure. TTS_2 is not a consistent measure of the effects of a single day's exposure to noise, and the NIPTS after many years may be quite different from the TTS_2 produced at the end of an 8-hour day. Research has failed to show a significant correlation between TTS and PTS (Burns and Robinson, 1970; Ward, 1980), and the relationships between TTS, PTS, and cochlear damage are equally unpredictable (Ward, 1970; Ward and Turner, 1982; Hetu, 1982; Clark and Bohne, 1978 and 1986).

CHABA's assumption of the equal temporary effect theory is also questionable in that some of the CHABA-permitted intermittent exposures can produce delayed recovery patterns even though the magnitude of the TTS was within "acceptable" limits, and chronic, incomplete recovery will hasten the advent of PTS. The CHABA criteria also assume regularly spaced noise bursts, interspersed with periods that are sufficiently quiet to permit the necessary amount of recovery from TTS. Both of these assumptions fail to characterize noise exposures in the manufacturing industries, although they may have some validity for outdoor occupations, such as forestry and mining.

The Botsford (1967) method, which represents a simplification of the CHABA criteria, is also, therefore, founded on dubious assumptions. The same can be said of the Intersociety Committee's simplifications of the original criteria developed by Glorig et al. (1961) and adopted by the ISO (1961), and the 5-dB rule as an outgrowth of all three sets of criteria. Although the origins of the 3-dB rule are somewhat unclear, the study of Burns and Robinson (1970) added to its credibility, and it has been increasingly supported by national and international consensus (EPA, 1973; EPA, 1974a and 1974b; ISO, 1971; ISO, 1990; and von Gierke et al., 1981). The only field study that has been repeatedly cited as supporting the 5-dB rule is the study of miners by Sataloff et al. (1969), the shortcomings of which have been described above.

Data from animal experiments support the use of the 3-dB exchange rate for single exposures of various levels within an 8-hour day (Ward and Nelson, 1971; Ward and Turner, 1982; Ward et al., 1983). But there is increasing evidence (Bohne and pearse, 1982; Ward and Turner, 1982; Ward et al., 1982; Bohne et al., 1985 and 1987; Clark, et al., 1987) that intermittency can be beneficial, especially in the laboratory. However, these benefits are likely to be smaller or even nonexistent in the industrial environment, where sound levels during intermittent periods are considerably higher and where interruptions are not evenly spaced.

Data from a number of field studies correspond well to the equal-energy rule, as Passchier-Vermeer (1971 and 1973) and Shaw (1985) have demonstrated. The fact that in Passchier-Vermeer's portrayal of the data, fewer points fall below the Burns and Robinson curve than below the Passchier-Vermeer curve seems to demonstrate the effect of Burns' and Robinson's rigorous screening procedures rather than support for any particular exchange rate. The fact that comparisons using the newer ISO standard corroborate Passchier-Vermeer's findings lend even greater support to the equal-energy rule.

Some field data from outdoor occupations, such as forestry and mining, show less hearing loss than expected when compared with continuous noise data (Sataloff et al., 1969; Holmgren et al., 1971; Johansson, 1973; and INRS, 1978), although these findings have not been supported by the two NIOSH (1976 and 1982) studies of intermittently exposed outdoor workers or the analyses conducted by Passchier-Vermeer (1973) and Shaw (1985). All of these studies may suffer from some of the methodological problems that plague epidemiological studies (such as inadequate characterization of exposure, sporadic wearing of protective equipment, and small sample size). If such a trend exists, it is further supported by the evidence with experimental animals that laboratory intermittencies produce a savings over continuous noise exposure.

But the ameliorative effect of intermittency does not support the use of the 5-dB exchange rate. For example, although Ward has noted that some industrial studies have shown lower NIPTS from intermittent noise exposure than would be predicted by the 3-dB rule, he did not favor selection of the 5-dB exchange rate as a compromise to compensate for the effects of intermittency because it would allow single exposures at excessively high levels. In his opinion, "this compromise was futile and perhaps even dangerous." (Ward, 1970)

One response to the evidence from the animal studies and certain field studies would be to select the 3-dB exchange rate, but to allow an adjustment (increase) to the maximum permissible exposure limit for outdoor, intermittent noise exposures, as suggested by EPA (1974a) and Johansson _et al_. (1973). This is in contrast to a 5-dB exchange rate, for which there is little scientific justification. Ideally, the amount of such an adjustment should be determined by the temporal pattern of the noise and the levels of quiet between noise bursts. At this time, however, there is little quantitative information about these parameters in real-world industrial noise environments. Until more of this kind of information becomes available, a conservative approach would be to allow a small increase, such as 2-dB, to the permissible exposure limit for outdoor occupations. This is the savings that Ward and Turner (1982) found for an on-fraction of 0.5.

The exact amount of such an adjustment should await clarification by further evidence. Moreover, the amount of the adjustment begins to become a policy rather than a scientific matter. If the permissible exposure limit is 90 dB, where some amount of hearing loss will occur in nearly every individual over a working lifetime (EPA, 1974a), then any such adjustment should be quite small. If, on the other hand, the permissible exposure limit is 85 dB, a larger adjustment would be acceptable. While the 3-dB rule may be somewhat conservative in truly intermittent conditions, the 5-dB rule will be under-protective in most others. Whether or not an adjustment is used for outdoor, intermittent exposures, it appears that the 3-dB exchange rate is the method most firmly supported by the scientific evidence for assessing hearing impairment as a function of noise level and duration.

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