Chapter 2

Introduction

2.1 Recognition of Noise as a Health Hazard

Noise, which is essentially any unwanted or undesirable sound, is not a new hazard. Indeed, NIHL has been observed for centuries. Before the industrial revolution, however, comparatively few people were exposed to high levels of workplace noise. The advent of steam power in connection with the industrial revolution first brought general attention to noise as an occupational hazard. Workers who fabricated steam boilers developed hearing loss in such numbers that the malady was dubbed "boilermaker's disease." Increasing mechanization in all industries and most trades has since proliferated the noise problem.

2.2 Noise-Induced Hearing Loss (NIHL)

NIHL is caused by exposure to sound levels or durations that damage the hair cells of the cochlea. Initially, the noise exposure may cause a temporary threshold shift—that is, a decrease in hearing sensitivity that typically returns to its former level within a few minutes to a few hours. Repeated exposures lead to a permanent threshold shift, which is an irreversible sensorineural hearing loss.

Hearing loss has causes other than occupational noise exposure. Hearing loss caused by exposure to nonoccupational noise is collectively called sociocusis. It includes recreational and environmental noises (e.g., loud music, guns, power tools, and household appliances) that affect the ear the same as occupational noise. Combined exposures to noise and certain physical or chemical agents (e.g., vibration, organic solvents, carbon monoxide, ototoxic drugs, and certain metals) appear to have synergistic effects on hearing loss [Hamernik and Henderson 1976; Brown et al. 1978; Gannon et al. 1979; Brown et al. 1980; Hamernik et al. 1980; Pryor et al. 1983; Rebert et al. 1983; Humes 1984; Boettcher et al. 1987; Young et al. 1987; Byrne et al. 1988; Fechter et al. 1988; Johnson et al. 1988; Morata et al. 1993; Franks and Morata 1996]. Some sensorineural hearing loss occurs naturally because of aging; this loss is called presbycusis. Conductive hearing losses, as opposed to sensorineural hearing losses, are usually traceable to diseases of the outer and middle ear.

Noise exposure is also associated with nonauditory effects such as psychological stress and disruption of job performance [Cohen 1973; EPA 1973; Taylor 1984; Öhrström et al. 1988; Suter 1989] and possibly hypertension [Parvizpoor 1976; Jonsson and Hansson 1977; Takala et al. 1977; Lees and Roberts 1979; Malchaire and Mullier 1979;

Manninen and Aro 1979; Singh et al. 1982; Belli et al. 1984; Delin 1984; Talbott et al. 1985; Verbeek et al. 1987; Wu et al. 1987; Talbott et al. 1990]. Noise may also be a contributing factor in industrial accidents [Cohen 1976; Schmidt et al. 1980; Wilkins and Acton 1982; Moll van Charante and Mulder 1990]. Nevertheless, data are insufficient to endorse specific damage risk criteria for these nonauditory effects.

2.3 Physical Properties of Sound

The effects of sound on a person depend on three physical characteristics of sound: amplitude, frequency, and duration. Sound pressure level (SPL), expressed in decibels, is a measure of the amplitude of the pressure change that produces sound. This amplitude is perceived by the listener as loudness. In sound-measuring instruments, weighting networks (described in Chapter 4) are used to modify the SPL. Exposure limits are commonly measured in dBA. When used without a weighted network suffix, the expression should be dB SPL.

The frequency of a sound, expressed in Hz, represents the number of cycles occurring in 1 sec and determines the pitch perceived by the listener. Humans with normal hearing can hear a frequency range of about 20 Hz to 20 kilohertz (kHz). Exposures to frequency ranges that are considered infrasonic (below 20 Hz), upper sonic (10 to 20 kHz), and ultrasonic (above 20 kHz) are not addressed in this document.

Although no uniformly standard definitions exist, noise exposure durations can be broadly classified as continuous-type or impulsive. All nonimpulsive noises (i.e., continuous, varying, and intermittent) are collectively referred to as "continuous-type noise." Impact and impulse noises are collectively referred to as "impulsive noise." Impulsive noise is distinguished from continuous-type noise by a steep rise in the sound level to a high peak followed by a rapid decay. In many workplaces, the exposures are often a mixture of continuous-type and impulsive sounds.

2.4 Number of Noise-Exposed Workers in the United States

In 1981, OSHA estimated that 7.9 million U.S. workers in the manufacturing sector were occupationally exposed to daily noise levels at or above 80 dBA [46 Fed. Reg.* 4078 (1981a)]. In the same year, the U.S. Environmental Protection Agency (EPA) estimated that more than 9 million U.S. workers were occupationally exposed to daily noise levels above 85 dBA, as follows:

**Federal Register*. See Fed. Reg. in references.

Major group	*Number of workers*
Agriculture	323,000
Mining	255,000
Construction	513,000
Manufacturing and utilities	5,124,000
Transportation	1,934,000
Military	976,000
Total	9,125,000

More than half of these workers were engaged in manufacturing and utilities [EPA 1981].

From 1981 to 1983, NIOSH conducted the National Occupational Exposure Survey (NOES), which was designed to provide data describing the occupational safety and health conditions in the United States [NIOSH 1988a,b, 1990]. The surveyors visited and gathered information at various workplaces throughout the United States. For the purposes of NOES, workers were considered noise-exposed if any noise (excluding impulsive noise) at or above 85 dBA occurred in their work environment at least once per week for 90% of the workweeks in a year [NIOSH 1988a]. Because not all industries were surveyed, NOES does not provide an all-inclusive estimate of the number of noise-exposed workers in the United States; however, it does provide reasonable estimates of the numbers of noise-exposed workers in the particular industries covered by NOES. These estimates are tabulated in Table 2-1, which shows that noise-exposed workers were employed in a wide range of industries, with the majority in manufacturing.

To collect occupational health data in mining industries not covered by NOES, NIOSH conducted the National Occupational Health Survey of Mining (NOHSM) from 1984 to 1989. Unlike NOES surveyors, the NOHSM surveyors did not measure the noise levels but used qualitative evaluation to determine noise exposures. As shown in Table 2-2, noise exposures occurred in all of the industries covered by NOHSM.

2.5 Legislative History

Efforts to regulate occupational noise in the United States began about 1955. The military was first to establish such regulations for members of the Armed Forces [U.S. Air Force 1956]. Under the Walsh-Healey Public Contracts Act of 1936, as amended, safety and health standards had been issued that contained references to excessive noise; however, they prescribed neither limits nor acknowledged the occupational hearing loss problem. A later regulation under this act [41 CFR 50-204.10], promulgated in 1969, defined noise limits that were applicable only to those firms having supply contracts with the U.S. Government greater than $10,000; similar limits were made applicable to work under Federal service contracts of $2,500 or more under the Service Contract Act. The noise rule in the Walsh-Healey Act regulations was adopted under the Federal Coal Mine Health and Safety Act of 1969 (Public Law 91-173) for underground and surface coal mine operations.

Table 2–1. Estimated number of workers exposed to noise at or above 85 dBA, by economic sector (two-digit SIC[*,†])

			Noise-exposed production workers	
Economic sector	SIC	Total number of production workers	Number	As % of total production workers
Agriculture, forestry, and fishing:				
Agriculture services	07	89,189	17,618	19.8
Mining:				
Oil and gas extraction	13	330,841	76,525	23.1
Construction:				
General building contractors	15	664,833	105,299	15.8
Heavy construction, except building	16	517,969	124,610	24.0
Special trade contractors	17	1,228,744	191,087	15.6
Manufacturing:				
Food and kindred products	20	1,188,267	343,030	28.9
Tobacco products	21	106,399	57,764	54.3
Textile mill products	22	615,322	262,108	42.6
Apparel and other finished products	23	1,082,236	150,824	13.9
Lumber and wood products	24	475,730	196,489	41.3
Furniture and fixtures	25	428,539	121,271	28.3
Paper and allied products	26	488,101	164,808	33.8
Printing and publishing	27	724,707	154,862	21.4
Chemicals and allied products	28	592,059	102,671	17.3
Petroleum and coal products	29	160,516	31,998	19.9
Rubber and miscellaneous plastics products	30	595,525	135,611	22.8
Leather and leather products	31	144,200	9,346	6.5
Stone, clay, and glass products	32	457,983	98,215	21.5
Primary metal industries	33	824,725	269,270	32.7
Fabricated metal products	34	1,151,777	336,919	29.3
Industrial machinery and equipment	35	1,544,883	229,509	14.9
Electronic and other electric equipment	36	1,287,842	104,553	8.1
Transportation equipment	37	1,311,750	238,609	18.2
Instruments and related products	38	555,108	48,014	8.7
Miscellaneous manufacturing industries	39	418,805	39,307	9.4

See footnotes at end of table.

(Continued)

Table 2-1 (Continued). Estimated number of workers exposed to noise at or above 85 dBA, by economic sector (two-digit SIC[*,†])

			Noise-exposed production workers	
Economic sector	**SIC**	**Total number of production workers**	**Number**	**As % of total production workers**
Transportation and public utilities:				
Local and inter-urban passenger transit	41	171,428	14,832	8.7
Trucking and warehousing	42	561,058	39,150	7.0
Transportation by air	45	312,931	94,656	30.3
Communications	48	387,505	23,124	6.0
Electric, gas, and sanitary services	49	588,041	89,730	15.3
Wholesale trade:				
Wholesale trade—durable goods	50	528,659	110,283	20.9
Wholesale trade—nondurable goods	51	99,410	5,287	5.3
Retail trade:				
Automotive dealers and service stations	55	334,063	4,543	1.4
Services:				
Personal services	72	366,545	33,462	9.1
Business services	73	766,108	11,246	1.5
Auto repair, services, and parking	75	320,459	33,997	10.6
Miscellaneous repair services	76	143,302	12,682	8.9
Health services	80	2,679,610	15,677	0.6
Total		24,245,169	4,098,986	16.9

---

[*] Standard industrial classification. Source: OMB [1987].

[†] Based on data collected by NOES [NIOSH 1988a,b, 1990]. Not all two-digit SIC sectors and not all four-digit SIC industries within each two-digit SIC sector were surveyed. The NOES covered 39 of 83 two-digit SIC sectors, and the NOES estimates were representative of only the four-digit SIC industries actually surveyed. For example, within agricultural services (SIC 07), the estimates are for crop preparation services (SIC 0723), veterinary services for animal specialties (SIC 0742), lawn and garden services (SIC 0782), and ornamental shrub and tree services (SIC 0783) only, because no surveys were done for soil preparation services (SIC 0711), crop planting and protecting (SIC 0721), crop harvesting (SIC 0722), cotton ginning (SIC 0724), veterinary services for livestock (SIC 0741), livestock services (SIC 0751), animal specialty services (SIC 0752), farm labor contractors (SIC 0761), farm management services (SIC 0762), and landscape counseling and planning (SIC 0781).

Table 2-2. Estimated number of workers exposed to noise, by industry (four-digit SIC[*])[†]

Industry	SIC	Total number of production workers	Noise-exposed production workers	
			Number	As % of total production workers
Iron ores	1011	3,614	3,411	94.4
Copper ores	1021	8,777	8,253	94.0
Lead and zinc ores	1031	1,363	1,190	87.3
Gold ores	1041	3,574	3,041	85.1
Silver ores	1044	1,893	1,503	79.4
Ferroalloy ores, except vanadium	1061	713	653	91.6
Uranium-radium-vanadium ores	1094	1,177	952	80.9
Miscellaneous metal ores, not elsewhere classified	1099	3,798	3,322	87.5
Bituminous coal and lignite mining	1220	123,274	108,264	87.8
Anthracite mining	1231	2,006	1,704	85.0
Crude petroleum and natural gas[‡]	1311	107	101	94.4
Dimension stone	1411	2,122	1,837	86.6
Crushed and broken limestone	1422	26,906	19,292	71.7
Crushed and broken granite	1423	4,545	3,643	80.2
Crushed and broken stone, not elsewhere classified	1429	5,796	4,829	83.3
Sand and gravel	1440	13,825	11,519	83.3
Clay, ceramic, and refractory minerals	1459	8,171	6,829	83.6
Potash, soda, and borate minerals	1474	4,855	4,258	87.7
Phosphate rock	1475	4,422	3,209	72.6
Chemical and fertilizer minerals	1479	2,175	1,297	59.6
Miscellaneous nonmetallic minerals	1499	4,755	3,586	75.4
Chemical preparation, not elsewhere classified[‡]	2899	263	250	95.1
Petroleum and coal products, not elsewhere classified[‡]	2999	42	23	54.8
Cement, hydraulic[‡]	3241	5,681	4,757	83.7
Lime[‡]	3274	2,529	2,014	79.6
Total	—	236,383	199,737	84.5

[*] Standard industrial classification. Source: OMB [1987].

[†] Based on data collected by NOHSM (unpublished data).

[‡] Estimates apply only to the miners—not the total workforce in this SIC industry.

In 1970, the Occupational Safety and Health Act (Public Law 95–164) was enacted, which established OSHA within the U.S. Department of Labor as the enforcement agency responsible for protecting the safety and health of a large segment of the U.S. workforce. Concurrently, NIOSH was established under the Department of Health, Education, and Welfare (now the Department of Health and Human Services) to develop criteria for safe occupational exposures to workplace hazards. In compliance with this provision, NIOSH published *Criteria for a Recommended Standard: Occupational Exposure to Noise* in 1972 [NIOSH 1972]. The document provided the basis for a recommended standard to reduce the risk of developing permanent noise-induced occupational hearing loss. The criteria document presented an REL of 85 dBA as an 8-hr TWA and methods for measuring noise, calculating noise exposure, and providing a hearing conservation program. However, the criteria document acknowledged that (1) NIOSH was not able to determine the technical feasibility of the REL, and (2) approximately 15% of the population exposed to occupational noise at the 85-dBA level for a working lifetime would develop occupational NIHL.

Initially, OSHA adopted the Walsh-Healey exposure limit of 90 dBA as an 8-hr TWA with a 5-dB exchange rate as its permissible exposure limit (PEL) [29 CFR 1910.95] for general industry. In 1974, responding to the NIOSH criteria document, OSHA proposed a revised noise standard [39 Fed. Reg. 37773 (1974a)] but left the PEL unchanged. The proposed standard was not promulgated; however, it articulated the requirement for a hearing conservation program. In 1981 and again in 1983, OSHA amended its noise standard to include specific provisions of a hearing conservation program for occupational exposures at 85 dBA or above [46 Fed. Reg. 4078 (1981a); 48 Fed. Reg. 9738 (1983)]. The OSHA noise standard as amended does not cover all industries. For example, the Hearing Conservation Amendments do not cover noise-exposed workers in transportation, oil/gas well drilling and servicing, agriculture, construction, and mining. The construction industry is covered by another OSHA noise standard [29 CFR 1926.52]; the mining industry is regulated by four separate standards that are enforced by MSHA [30 CFR 56.5050; 30 CFR 57.5050; 30 CFR 70.500–70.508; 30 CFR 71.800–71.805]. These standards vary in specific requirements regarding exposure monitoring and hearing conservation; however, all maintain an exposure limit based on 90 dBA for an 8-hr duration. Although they are required to comply with OSHA regulations by Executive Order 12196, the U.S. Air Force [1993] and the U.S. Army [1994] have chosen a more stringent exposure limit of 85 dBA as an 8-hr TWA with a 3-dB exchange rate. Thus, the protection that a worker receives from occupational noise depends in part on the sector in which he or she is employed.

The exposure limits discussed above apply only to continuous-type noises. For impulsive noise, the generally accepted limit not to be exceeded for any time is a peak level of 140 dB SPL. Among the regulatory standards, this peak level is either enforceable or nonenforceable, as indicated by the word "shall" or "should," respectively. For example, in the MSHA standards for metal and nonmetal mines [30 CFR 56.5050; 30 CFR 57.5050], this exposure limit is enforceable; in the OSHA standards [29 CFR 1910.95; 29 CFR 1926.52], it is nonenforceable.

2.6 Scope of This Revision of the Noise Criteria Document

The focus of this document is on the prevention of occupational hearing loss rather than on conservation. Prevention means to avoid creating hearing loss. Conservation means to sustain the hearing that is present, regardless of whether damage has already occurred. An emphasis on prevention evolves from beliefs that it should not be necessary to suffer an impairment, illness, or injury to earn a living and that it is possible to use methods to prevent occupational hearing loss. This document evaluates and presents recommended exposure limits, a 3-dB exchange rate, and other elements necessary for an effective HLPP. Where the information is incomplete to support definitive recommendations, research needs are suggested for future criteria development. Nonauditory effects of noise and hearing losses due to causes other than noise are beyond the scope of this document.

CHAPTER 3

Basis for the Exposure Standard

3.1 Quantitative Risk Assessment

The selection of an exposure limit depends on the definitions of two parameters: (1) the maximum acceptable occupational hearing loss (i.e., the fence) and (2) the percentage of the occupational noise-exposed population for which the maximum acceptable occupational hearing loss will be tolerated. The fence is often defined as the average HTL for two, three, or four audiometric frequencies. It separates the maximum acceptable hearing loss from smaller degrees of hearing loss and normal hearing. Excess risk is the difference between the percentage that exceeds the fence in an occupational-noise-exposed population and the percentage that exceeds it in an unexposed population. Mathematical models are used to describe the relationship between excess risk and various factors such as average daily noise exposure, duration of exposure, and age group.

The most common protection goal is the preservation of hearing for speech discrimination. Using this protection goal, NIOSH [1972] employed the term "hearing impairment" to define its criteria for maximum acceptable hearing loss; and OSHA later used the slightly modified term "material hearing impairment" to define the same criteria [46 Fed. Reg. 4078 (1981a)]. In this context, a worker was considered to have a material hearing impairment when his or her average HTLs for *both* ears exceeded 25 dB at the audiometric frequencies of 1000, 2000, and 3000 Hz (denoted here as the "1-2-3-kHz definition").

3.1.1 NIOSH Risk Assessment in 1972

NIOSH [1972] assessed the *excess* risk of material hearing impairment as a function of levels and durations (e.g., 40-year working lifetime) of occupational noise exposure. Thus, for a 40-year lifetime exposure in the workplace to average daily noise levels of 80, 85, or 90 dBA, the excess risk of material hearing impairment was estimated to be 3%, 16%, or 29%, respectively. On the basis of this risk assessment, NIOSH recommended an 8-hr TWA exposure limit of 85 dBA [NIOSH 1972].

To compare the NIOSH excess risk estimates with those developed by other organizations, the NIOSH data were also analyzed using the same 25-dB fence, but averaging the HTLs at 500, 1000, and 2000 Hz (the 0.5-1-2-kHz definition) [NIOSH 1972]. Table 3-1 presents the excess risk estimates developed by NIOSH [1972], EPA [1973], and the International Standards Organization (ISO) [1971] for material hearing impairment caused by occupational noise exposure. OSHA used these estimates as the basis for requiring hearing conservation programs for occupational noise exposures at or above 85 dBA (8-hr TWA) [46 Fed. Reg. 4078 (1981a)].

Table 3–1. Estimated excess risk of incurring material hearing impairment[*] as a function of average daily noise exposure over a 40-year working lifetime[†]

Reporting organization	Average daily noise exposure (dBA)	Excess risk (%)[‡]
ISO	90	21
	85	10
	80	0
EPA	90	22
	85	12
	80	5
NIOSH	90	29
	85	15
	80	3

[*] For purposes of comparison in this table, material hearing impairment is defined as an average of the HTLs for both ears at 500, 1000, and 2000 Hz that exceeds 25 dB.

[†] Adapted from 39 Fed. Reg. 43802 [1974b].

[‡] Percentage with material hearing impairment in an occupational-noise-exposed population after subtracting the percentage who would normally incur such impairment from other causes in an unexposed population.

The data used for the NIOSH risk assessment were collected by NIOSH in 13 noise and hearing surveys (collectively known as the Occupational Noise and Hearing Survey [ONHS]) from 1968 to 1971. The industries in the surveys included steelmaking, paper bag processing, aluminum processing, quarrying, printing, tunnel traffic controlling, woodworking, and trucking. Questionnaires and audiometric examinations were given to noise-exposed and non-noise-exposed workers who had consented to participate in the surveys. More than 4,000 audiograms were collected, but the sample excluded audiograms of (1) noise-exposed workers whose noise exposures could not be characterized relative to a specified continuous noise level over their working lifetime, and (2) noise-exposed workers with abnormal hearing levels as determined by their medical history. Thus, 1,172 audiograms were used. These represented 792 noise-exposed and 380 non-noise-exposed workers (controls) [NIOSH 1972; Lempert and Henderson 1973].

3.1.2 NIOSH Risk Assessment in 1997

A review of relevant epidemiologic literature did not identify new data suitable for estimating the excess risk of occupational NIHL for U.S. workers. The prolific use of hearing protectors in the U.S. workplace since the early 1980's would confound determination of dose-response relationships for occupational NIHL among contemporary workers. Therefore, the current risk assessment is based on a reanalysis of data from the NIOSH ONHS [Prince et al. 1997].

Prince et al. [1997] (reprinted in the Appendix of this document) derived a new set of excess risk estimates using the ONHS data with a model referred to as the "1997-NIOSH model," which differed from the 1972-NIOSH model [NIOSH 1972]. A noteworthy difference between the two models is that Prince et al. [1997] considered the possibility of nonlinear effects of noise in the 1997-NIOSH model, whereas the 1972-NIOSH model was based solely on a linear assumption for the effects of noise. Table 3–2 provides an overview of the differences between the 1997- and the 1972-NIOSH models. Prince et al. [1997] found that nonlinear models fit the data well and that the linear models similar to the 1972-NIOSH model did not fit as well. In addition to using the 0.5-1-2-kHz and the 1-2-3-kHz definitions of material hearing impairment to assess the risk of occupational NIHL, Prince et al. [1997] used the definition of hearing handicap* proposed by the American Speech-Language-Hearing Association (ASHA) Task Force on the Definition of Hearing Handicap. Prince et al. [1997] found the ASHA Task Force definition† (average of HTLs at 1000, 2000, 3000, and 4000 Hz) [ASHA 1981] useful because it was geared toward excess risk of hearing loss rather than compensation. Phaneuf et al. [1985] also found that the audiometric average of 1000, 2000, 3000, and 4000 Hz provided "a superior prediction of hearing disability in terms of specificity, sensitivity, and overall accuracy." The ASHA Task Force definition is also referred to as the 1-2-3-4-kHz definition in this criteria document. Table 3–3 presents the excess risk estimates for this definition and associated 95% confidence intervals.

The ISO has also developed procedures for estimating hearing loss due to noise exposure. In 1971, the ISO issued the first edition of *ISO 1999, Assessment of Occupational Noise Exposure for Hearing Conservation Purposes* [ISO 1971] (referred to as the "1971-ISO model"), which included risk estimates for material hearing impairment from occupational noise exposures. In 1990, the ISO issued a second edition of *ISO 1999, Acoustics—Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment* [ISO 1990] (referred to as the "1990-ISO model"). Both ISO models are based on broadband, steady noise exposures for 8-hr work shifts during a working lifetime of up to 40 years.

The various models for estimating the excess risk of material hearing impairment are compared in Table 3–4. The excess risk estimates derived from the 1971-ISO, 1972-NIOSH, 1973-EPA, and 1997-NIOSH‡ models are reasonably similar. However,

---

*ASHA makes a distinction between the terms "impairment" and "handicap"; however, for the purpose of the subsequent discussion in this criteria document, only the term "material hearing impairment" is used. The Prince et al. [1997] paper reports the use of a modified ASHA Task Force definition. This modification incorporates frequency-specific weights based on the articulation index for each frequency [ANSI 1969]. Negligible differences were found between excess risk estimates generated using the modified and the unmodified definitions. The excess risk estimates presented in this criteria document are based on the unmodified ASHA Task Force definition.

†Historical note, ASHA did not deliberate on the definition proposed by the ASHA Task Force.

‡Prince et al. [1997] found that the excess risk estimates at exposure levels below 85 dBA were not well defined. Insufficient data for workers with average daily exposures below 85 dBA led to considerable variability in the estimation, depending on the statistical assumptions used in the modeling.

Table 3–2. Comparison of the 1997– and 1972–NIOSH risk-damage models

Item	Description 1997–NIOSH model	 1972–NIOSH model
Model	Logit model: Dichotomous outcome[*] Model probability of hearing impairment directly	Probit model: Continuous outcome (average HTL) Model distribution of HTL and calculate percentage of population meeting impairment criteria
Sound level effect	Dependent on duration of exposure $\beta [L_e\text{-}L_0]^\phi$ L_0 (control sound level) and ϕ (shape of dose-response curve) are estimated from the data L_e=Sound level in exposed population Model allows flexibility in determining shape of dose-response curve and location of control sound levels	Dependent on duration of exposure $\beta [L_e\text{-}L_0]^1$ L_0 and ϕ are fixed values ϕ=1 assumes a linear dose-response relationship L_e=Sound level in exposed population
Age, years	Modeled as a continuous variable	Modeled as a categorical variable with five levels (17–27, 28–35, 36–45, 46–54, 55–70)
Duration of exposure, years	Modeled as a categorical variable with 4 levels (<2, 2–4, 5–10, >10)	Modeled as a categorical variable with five levels (<2, 2–4, 5–10, 11–20, 21–41)

[*] Each individual is categorized either as hearing-impaired (defined as average HTL >25 dB, both ears) or non-hearing-impaired (average HTL ≤25 dB).

except for the 1-2-3-4-kHz definition, the excess risk estimates derived from the 1990-ISO model are considerably lower than those derived from the other models. These disparities may be due to differences in the statistical methodology or in the underlying data used. Nevertheless, these five models confirm an excess risk of material hearing impairment at 85 dBA.

As mentioned earlier in this section, the protection goal incorporated in the definitions of material hearing impairment has been to preserve hearing for speech discrimation. The 4000-Hz audiometric frequency is recognized as being both sensitive to noise and important for hearing and understanding speech in unfavorable or noisy listening conditions [Kuzniarz 1973; Aniansson 1974; Suter 1978; Smoorenburg 1990]. In recognition of the fact that listening conditions are not always ideal in everyday life, and in concurrence with the ASHA [1981] Task Force proposal, NIOSH has modified its

Table 3–3. Excess risk estimates for material hearing impairment,[*] by age and duration of exposure

	5–10 years of exposure								>10 years of exposure							
	Age 30		Age 40		Age 50		Age 60		Age 30		Age 40		Age 50		Age 60	
Average daily exposure (dbA)	Risk (%)	95% CI[†]	Risk (%)	95% CI	Risk (%)	95% CI	Risk (%)	95% CI	Risk (%)	95% CI	Risk (%)	95% CI	Risk (%)	95% CI	Risk (%)	95% CI
90	5.4	2.1–9.5	9.7	3.7–16.5	14.3	5.5–24.4	15.9	6.2–26.2	10.3	5.8–16.2	17.5	10.7–25.3	24.1	14.6–33.5	24.7	14.9–34.3
85	1.4	0.3–3.2	2.6	0.6–6.0	4.0	0.9–9.3	4.9	1.0–11.5	2.3	0.7–5.3	4.3	1.3–9.4	6.7	2.0–13.9	7.9	2.3–16.6
80	0.2	0–1.1	0.4	0–2.2	0.6	0.01–3.6	0.8	0.01–4.7	0.3	0–1.8	0.6	0.01–3.3	1.0	0.01–5.2	1.3	0.01–6.8

[*] 1997–NIOSH model for the 1-2-3-4-kHz definition of hearing impairment.

[†] CI=confidence interval.

Table 3-4. Comparison of models for estimating the excess risk of material hearing impairment at age 60 after a 40-year working lifetime exposure to occupational noise, by definition of material hearing impairment

Average exposure level (dBA)	0.5-1-2-kHz definition					1-2-3-kHz definition			1-2-3-4-kHz definition	
	1971-ISO	1972-NIOSH	1973-EPA	1990-ISO	1997-NIOSH	1972-NIOSH	1990-ISO	1997-NIOSH	1990-ISO	1997-NIOSH
90	21	29	22	3	23	29	14	32	17	25
85	10	15	12	1	10	16	4	14	6	8
80	0	3	5	0	4	3	0	5	1	1

definition of material hearing impairment to include 4000-Hz when assessing the risk of occupational NIHL. Therefore, with this modification, NIOSH defines material hearing impairment as an average of the HTLs for both ears that exceeds 25 dB at 1000, 2000, 3000, and 4000 Hz. Based on this definition, the excess risk is 8% for workers exposed to an average daily noise level of 85 dBA over a 40-year working lifetime. NIOSH continues to recommend the REL of 85 dBA as an 8-hr TWA on the basis of (1) analyses supporting the 1972 REL of 85 dBA as an 8-hr TWA, (2) reanalyses of the ONHS data, (3) ASHA Task Force positions on preservation of speech discrimination, and (4) analyses of excess risk of ISO, EPA, and NIOSH databases.

For extended work shifts (i.e., greater than 8 hr), lower exposure limits can be extrapolated from the REL of 85 dBA as an 8-hr TWA (see Section 1.1.1 or Table 1-1). Stephenson et al. [1980] studied human responses to 24-hr noise exposures and found that no temporary threshold shift occurred for broadband noise exposures less than 75 to 80 dBA. These data are in line with the recommendation that TWA exposures be less than 80 to 81 dBA for durations greater than 16 hr.

3.2 Ceiling Limit

Because NIOSH is recommending a 3-dB exchange rate with an 85-dBA REL, a ceiling limit for continuous-type noise is unnecessary. For example, with an 85-dBA REL and a 3-dB exchange rate, an exposure duration of less than 28 sec would be allowed at a 115-dBA level.

The generally accepted ceiling limit of 140 dB peak SPL for impulsive noise is based on a report by Kryter et al. [1966]. Ward [1986] indicated that "this number was little more than a guess when it was first proposed." To date, a proposal for a different limit has not been supported. Henderson et al. [1991] indicated that the critical level for chinchillas is between 119 and 125 dB; and if a 20-dB adjustment is used to account for the difference in susceptibility between chinchillas and humans, the critical level extrapolated for humans would be between 139 and 145 dB. Based on the 85-dBA REL and the 3-dB exchange rate, the allowable exposure time at 140 dBA is less than 0.1 sec; thus, 140 dBA is a reasonable ceiling limit for impulsive noise.

3.3 Exchange Rate

Health effects depend on exposure level and duration. The NIOSH recommendation for a 3-dB exchange rate is based in part on the conclusions from a NIOSH contract report [Suter 1992a]. This report involved an exhaustive analysis of the relationship between hearing loss, noise level, and exposure duration. Although the time/intensity relationship is most commonly referred to as the exchange rate, it is also referred to as the "doubling rate," "trading ratio," and "time-intensity tradeoff." The 3-dB exchange rate is also known as the equal-energy rule or hypothesis, because a 3-dB increase/decrease represents a doubling or halving of the sound energy. The most commonly used exchange rates incorporate either 3 dB or 5 dB per doubling or halving of exposure duration [Embleton 1994].

The 3-dB exchange rate is the method most firmly supported by scientific evidence for assessing hearing impairment as a function of noise level and duration. This rate is already used in the United States by the EPA and the U.S. Department of Defense. The 3-dB exchange rate is used worldwide by nations such as Canada, Australia, New Zealand, the People's Republic of China, the United Kingdom, Germany, and many others. First proposed by Eldred et al. [1955], the 3-dB exchange rate was later supported by Burns and Robinson [1970]. The premise behind the 3-dB exchange rate is 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. However, Ward and Turner [1982] suggest restricting its use to the sound energy accumulated in 1 day. They distinguish between (1) an interpretation of the total energy theory that would allow an entire lifetime of exposure to be condensed into a few hours and (2) a restricted equal-A-weighted-daily-energy interpretation of the theory. Burns [1976] also cautions against the misuse of the equal-energy hypothesis, noting that it was based on data gathered from workers who experienced 8-hr occupational exposures daily for periods of months to years; thus, extrapolation to very different conditions would be inappropriate.

In 1973, the U.S. Air Force adopted a 4-dB exchange rate [U.S. Air Force 1973]. This exchange rate is based on an unpublished analysis by H.O. Parrack at the Aerospace Medical Research Laboratory. However, a set of curves based on this analysis was published as Figure 20 in a joint EPA/Air Force report [Johnson 1973]. The 4-dB exchange rate came closest to the curve that best described temporary theshold shift at 1000-Hz audiometric frequency [Johnson 1973]. However, Johnson [1973] also pointed out that according to these curves, the 3-dB exchange rate would best protect hearing at the 4000-Hz frequency, and the 5-dB exchange rate would be a good compromise if hearing were to be protected only at the midfrequencies—500, 1000, and 2000 Hz.

The relationship between the 3-dB exchange rate and energy can be illustrated as follows. The *American National Standard for Acoustical Terminology*, ANSI S1.1–1994 [ANSI 1994] defines the decibel as a "unit of level when the base of the logarithm is the tenth root of ten, and the quantities concerned are proportional to power.... [E]xamples of quantities that qualify are power (in any form), sound pressure squared, particle velocity squared, sound intensity, sound-energy density, and voltage squared. Thus, the decibel is a unit of sound-pressure-squared level; it is common practice, however, to shorten this to sound pressure level, when no ambiguity results from so doing."

Ostergaard [1986] provided a functional elucidation of the relationships pointed to in the ANSI definition:

> In acoustics, decibel notation is utilized for most quantities. The *decibel* is a dimensionless unit based on the logarithm of the ratio of a measured quantity to a reference quantity. Thus, decibels are defined as follows:
>
> $$L = k \log_{10} (A/B)$$
>
> where L is the level in decibels, A and B are quantities having the same units, and k is a multiplier, either 10 or 20 depending on whether A and B are measures of energy or pressure, respectively. Any time a level is referred to in acoustics, decibel notation is implied. In acoustics all *levels* are referred to some reverence quantity, which is the denominator, B, of the equation.

Applying this mathematical relationship in the following calculations demonstrates how every doubling of energy yields an increase of 3 dB:

Let X = the exchange rate whereby energy is doubled
$10 \text{ Log}_{10} (A/B) + X = 10 \text{ Log}_{10} (2A/B)$
$X = 10 \text{ Log}_{10} (2A/B) - 10 \log_{10} (A/B)$
$= 10 \text{ Log}_{10} (2)$
$= 10 (0.301)$
$= 3.01$ dB

This same relationship does not hold true for the 5-dB exchange rate. To derive $X = 5$ dB, the sound intensity would have to be more than doubled in this equation. Thus, the 5-dB exchange rate does not provide for the doubling or halving of energy per 5-dB increment.

The 5-dB exchange rate is sometimes called the OSHA rule; it is less protective than the equal-energy hypothesis. The 5-dB exchange rate attempts to account for the interruptions in noise exposures that commonly occur during the workday [40 Fed. Reg. 12336 (1975)], presuming that some recovery from temporary threshold shift occurs during these interruptions and the hearing loss is not as great as it would be if the noise were continuous. The rule makes no distinction between continuous and noncontinuous noise, and it will permit comparatively long exposures to continuous noise at higher sound levels than would be allowed by the 3-dB rule. On the basis of the limited data that existed in the early 1970's, NIOSH [1972] recommended the 5-dB exchange rate; however, after reviewing the more recent scientific evidence, NIOSH now recommends the 3-dB exchange rate.

The evolution of the 5-dB exchange rate began in 1965 when the Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) for the National Academy of Sciences–National Research Council issued criteria for assessing allowable exposures to continuous, fluctuating, and intermittent noise [Kryter et al. 1966]. The CHABA criteria were an attempt to predict the hazard from nearly every conceivable noise exposure pattern based on temporary threshold shift experimentation. In the development of its criteria, CHABA used the following postulates:

1. TTS_2 (temporary threshold shift measured 2 min after a period of noise exposure) is a consistent measure of the effects of a single day of exposure to noise.

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

3. Permanent threshold shift produced after many years of habitual noise exposures for 8 hr per day is about the same as the TTS_2 produced in normal ears by an 8-hr exposure to the same noise.

However, these CHABA postulates were not validated. Research has been unable to demonstrate a simple relationship between temporary threshold shift, permanent threshold shift, and cochlear damage [Burns and Robinson 1970; Ward 1970, 1980; Ward and Turner 1982; Hétu 1982; Clark and Bohne 1978, 1986]. The CHABA criteria assumed that worker exposures could be characterized by regularly spaced noise bursts interspersed with periods that were sufficiently quiet to allow hearing to recover. However, this assumption is not characteristic of many typical industrial noise exposures. Workers will always develop temporary threshold shift before sustaining permanent threshold shift, barring an ototraumatic incident. Temporary threshold shift is a useful metric for monitoring the effects of noise exposure; these studies do not imply otherwise.

In general, the CHABA hearing damage risk criteria proved too complicated for general use. Botsford [1967] published a simplified set of criteria based on the CHABA criteria. One of the simplifications inherent to the Botsford [1967] method was the assumption that interruptions would be of "equal length and spacing so that a number of identical exposure cycles would be distributed uniformly throughout the day." These interruptions would occur during coffee breaks, trips to the washroom, lunch, and periods when machines were temporarily shut down.

During the same period, another related development led to the 5-dB exchange rate. Simplifying the criteria developed by Glorig et al. [1961] and adopted by ISO [1961], the Intersociety Committee [1970] published its criteria, which consisted of a table showing permissible exposure levels (starting at 90 dBA) as a function of duration and the number of occurrences per day. The exchange rates varied considerably depending on noise level and frequency of occurrence. For continuous noise with durations of less than 8 hr, the Committee recommended maximum exposure levels based on a 5-dB exchange rate. The only field study that has been repeatedly cited as supporting the 5-dB rule is one study of coal miners by Sataloff et al. [1969].

In 1969, the U.S. Department of Labor promulgated a noise standard [34 Fed. Reg. 790 (1969a)] under the authority of the Walsh-Healey Public Contracts Act. The standard contained a PEL of 90 dBA for continuous noise. Exposure to varying or intermittent noise was to be assessed over a weekly period according to a large table of exposure indices. 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 was used for short-duration, high-level bursts. This standard was withdrawn after a short period. Later in 1969, the Walsh-Healey noise standard that is in effect today was issued [34 Fed. Reg. 7948 (1969b)]. In this version, any special criteria for varying or intermittent noise had disappeared, and the 5-dB exchange rate became official. Thus, the 5-dB exchange rate appears to have been the outgrowth of the many simplifying processes that preceded it.

Beginning with the study of Burns and Robinson [1970], the credibility of the 3-dB rule has been increasingly supported by numerous studies and by national and international consensus [EPA 1973, 1974; 39 Fed. Reg. 43802 (1974b); ISO 1971; von Gierke et al. 1981; ISO 1990; U.S. Air Force 1993; U.S. Army 1994; ACGIH 1995].

Data from a number of field studies correspond well to the 3-dB rule (equal-energy hypothesis), as Passchier-Vermeer [1971, 1973] and Shaw [1985] have demonstrated. In Passchier-Vermeer's [1973] portrayal of the data, the Passchier-Vermeer [1968] and the Burns and Robinson [1970] prediction models for hearing losses as a function of continuous-noise exposure level fit the data on hearing losses from varying or intermittent noise exposures quite well. The fact that comparisons using the newer ISO standard [ISO 1990] corroborate Passchier-Vermeer's findings lend additional support to the equal-energy hypothesis.

Some older field data from occupations such as forestry and mining show less hearing loss than expected when compared with equivalent levels of continuous noise [Sataloff et al. 1969; Holmgren et al. 1971; Johansson et al. 1973; INRS 1978]. However, these findings have not been supported by the two NIOSH [1976, 1982] studies of intermittently exposed workers or the analyses conducted by Passchier-Vermeer [1973] and Shaw [1985].

Data from animal experiments support the use of the 3-dB exchange rate for single exposures of various levels within an 8-hr day [Ward and Nelson 1971; Ward and Turner

1982; Ward et al. 1983]. Nevertheless, several animal studies have demonstrated that some recovery may occur during the "quiet" periods of an intermittent noise exposure [Bohne and Pearse 1982; Ward and Turner 1982; Ward et al. 1982; Bohne et al. 1985; Bohne et al. 1987; Clark et al. 1987]. However, these benefits are likely to be smaller or even nonexistent in the industrial environment, where sound levels during quiet periods are considerably higher and where interruptions are not evenly spaced.

The possible ameliorative effect of intermittency does not justify the use of the 5-dB exchange rate. For example, although Ward [1970] noted that some industrial studies have shown lower permanent threshold shifts 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 PEL for certain intermittent noise exposures, as suggested by EPA [1974] and Johansson et al. [1973]. This response would be in contrast to a 5-dB exchange rate, for which there is little scientific justification. Ideally, if an adjustment is needed, the amount should be determined by the temporal pattern of the noise and the levels of quiet between noise bursts. At this time, however, little quantitative information is available about these parameters in industrial environments. Therefore, the need for an adjustment should be clarified by further research. Although the 3-dB rule may be somewhat conservative in truly intermittent conditions, the 5-dB rule will be underprotective in most others. 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, whether or not an adjustment is used for certain intermittent exposures.

3.4 Impulsive Noise

The OSHA occupational noise standard [29 CFR 1910.95] states: "Exposure to impulsive or impact noise should not exceed 140 dB peak sound pressure." Thus, in this context, the 140-dB limit is advisory rather than mandatory. This number was first proposed by Kryter et al. [1966] and later acknowledged by Ward [1986] as little more than a guess. NIOSH [1972] did not address the hazard of impulsive (i.e., impulse or impact) noise, although NIOSH stated that the provisions of the recommended standard in the criteria document were intended to apply for all noise. Although there is yet no unanimity as to which criteria best describe the relationship between NIHL and exposure to impulsive noise, either by itself or in the presence of continuous-type (i.e., continuous, varying, or intermittent) noise, there is an international standard that has become widely used by most industrial nations. This standard, *ISO 1999, Acoustics—An Estimation of Noise-Induced Hearing Impairment* [ISO 1990], integrates both impulsive and continuous-type noise (and uses the 3-dB exchange rate of the equal-energy rule) when calculating sound exposures over any specified time period. NIOSH concurs with this approach and recommends that noise exposure levels be calculated by integrating all noises (both impulsive and continuous-type) over the duration of the measurement.

Despite its simplicity, the equal-energy rule is not universally accepted as a method for characterizing exposures that consist of both impulsive and continuous-type noises. Another approach favors evaluating impulsive noise separate from that of continuous-type noise. Studies that would argue for this approach will be discussed first, followed by a discussion of studies elucidating the rationale for the NIOSH position on the equal-energy rule.

3.4.1 Evidence That Impulsive Noise Effects Do Not Conform to the Equal-Energy Rule

In her evaluation of the effects of continuous and varying noises on hearing, Passchier-Vermeer [1971] found that the HTLs of workers in steel construction works did not conform to the equal-energy hypothesis; that is, the hearing losses in these workers, who were exposed to noise levels with impulsive components, were higher than predicted. Later studies by Ceypek et al. [1973], Hamernik and Henderson [1976], and Nilsson et al. [1977] also indicated that continuous and impulsive noises have a synergistic rather than additive effect on hearing.

Comparing the studies of Passchier-Vermeer [1973] and of Burns and Robinson [1970], Henderson and Hamernik [1986] suggested that the steeper slope of Passchier-Vermeer's exposure-response curve at the 4000-Hz audiometric frequency might have been due to noise exposures that contained impulsive components, a characteristic not present in the Burns and Robinson data. Citing the similarity of Passchier-Vermeer's data to those collected by Taylor et al. [1984] and Kuzniarz et al. [1976] on workers exposed to impulsive noise environments, Henderson and Hamernik [1986] indicated that exposure to continuous and impulsive noises in combination may be more hazardous than exposure to continuous noise alone.

Voight et al. [1980] studied noise exposure patterns in the building construction industry and related the equivalent continuous sound level for 8 hr (L_{Aeq8hr})to audiometric records of more than 81,000 construction workers in Sweden. They found differences in hearing loss among groups exposed to noise of the same L_{Aeq8hr} but with different temporal characteristics. Groups exposed to impulsive noise had more hearing loss than those exposed to continuous noise of the same L_{Aeq8hr}.

Sulkowski and Lipowczan [1982] conducted noise measurement and audiometric testing in a drop-forge factory. The HTLs of 424 workers in the factory were compared with the predicted values according to the Burns and Robinson equation [1970]. The observed and predicted values differed in that the observed hearing loss was smaller than predicted at the lower audiometric frequencies, but the observed hearing loss was greater than predicted at the higher audiometric frequencies. In their study of hearing loss in weavers, who were exposed to continuous noise, and drop-forge hammer men, who were exposed to impact noise of equivalent energy, Sulkowski et al. [1983] found that the hammer men had substantially worse hearing than the weavers.

Thiery and Meyer-Bisch [1988] conducted a cross-sectional epidemiologic study at an automobile manufacturing plant. The automotive workers were exposed to continuous and impulsive noises at L_{Aeq8hr} ranging from 87 to 90 dBA. When their HTLs were compared with those of workers exposed to continuous noise at L_{Aeq8hr} of 95 dBA for the same exposure time, the automotive workers showed greater hearing losses at the 6000 -Hz audiometric frequency than the reference population after 9 years of exposure.

Starck et al. [1988] compared at the 4000-Hz audiometric frequency the HTLs of forest workers using chain saws and shipyard workers using hammers and chippers. The forest workers were exposed to continuous-type noise, whereas the shipyard workers were exposed to impact noise. Starck et al. [1988] also used the immission model developed by Burns and Robinson [1970] to predict the HTLs for both groups. They found that the Burns and Robinson model was accurate at 4000 Hz for the forest workers; however, it substantially underestimated the HTLs at 4000 Hz for the shipyard workers.

The studies described here provide evidence that the effects of combined exposure to impulsive and continuous-type noises are synergistic rather than additive, as the equal-energy hypothesis would support. One measure for protecting a worker from such synergistic effects would be to require that a correction factor be added to a measured TWA noise exposure level when impulsive components are present in the noise. The magnitude of such a correction has not been quantified. The matter becomes more complicated when other parameters of impulsive noise are considered. Noise energy does not appear to be the only factor that affects hearing. The amplitude, duration, rise time, number of impulses, repetition rate, and crest factor also appear to be involved [Henderson and Hamernik 1986; Starck and Pekkarinen 1987; Pekkarinen 1989]. The criteria for exposure to impulsive noise based on the interrelationships of these parameters await the results of further research.

3.4.2 Evidence That Impulsive Noise Effects Conform to the Equal-Energy Rule

In 1968, CHABA published damage risk criteria for impulsive noise based on the equal-energy hypothesis [Ward 1968]. Over the years, individuals and organizations have supported treating impulsive noise on an equal-energy basis [Coles et al. 1973; EPA 1974; Coles 1980; ISO 1990].

Burns and Robinson [1970] proposed the concept of immission, which is based on the equal-energy hypothesis, to describe the total energy from a worker's exposure to continuous noise over a period of time (i.e., months or years). Atherley and Martin [1971] modified this concept to include impulsive noise in the calculation of the L_{Aeq8hr}.

In a study of 76 men who were exposed to impact noise in two drop-forging factories, Atherley and Martin [1971] calculated each man's noise exposure (immission level) during his employment period and plotted it against his age-corrected HTLs over six audiometric frequencies. They found that the observed HTLs of the population came close to the predicted HTLs according to Robinson [1968] and concluded that the equal-energy hypothesis was applicable to impact noise. Similarly, Atherley [1973] examined the HTLs of 50 men exposed to impact noise produced by pneumatic chisels used on metal castings and found good agreement between observed and predicted HTLs.

Guberan et al. [1971] compared the HTLs of 70 workers exposed to impact noise in drop-forging workshops with the predicted HTLs according to Robinson [1968] at the 3-, 4-, and 6-kHz audiometric frequencies. Again, the observed HTLs were in close agreement with the predicted HTLs.

A study of 716 hammer and press operators in 7 drop forges by Taylor et al. [1984] indicated that hearing losses resulting from impact and continuous noises in the drop-forging industry were as great or greater than those resulting from equivalent continuous noise. Using noise dosimetry, Taylor et al. [1984] found that the hammer operators were exposed to an average L_{Aeq8hr} of 108 dBA, whereas the press operators were exposed to 99 dBA. The investigators also conducted audiometry for the operators. The median HTLs of hammer operators of all age groups approximated those predicted by the Robinson [1968] immission model. The median HTLs of younger press operators (aged 15 to 34) also corresponded closely with the predicted values; however, those of older press operators (aged 34 to 54) were significantly higher than predicted. These results indicate that, up to certain limits, the equal-energy hypothesis can be applied to combined exposure to impact and continuous noises.

3.4.3 Combined Exposure to Impulsive and Continuous-Type Noises

In many industrial operations, impulsive noise occurs in concert with a background of continuous-type noise. In some animal studies the effects of combined exposure to continuous-type and impulsive noises appear to be synergistic at high exposure levels [Hamernik et al. 1974]. But the synergism disappears when the exposure levels are comparable with those found in many common industrial environments [Hamernik et al. 1981]. Whether the effects of combined exposure are additive or synergistic, exposure to these noises causes hearing loss; thus the contribution of impulse noise to the noise dose should not be ignored. If the effects are additive, the 85-dBA REL with the 3-dB exchange rate would be sufficiently protective. If the effects are synergistic, the same would still be protective to a smaller extent. NIOSH therefore recommends that the REL of 85 dBA as an 8-hr TWA be applicable to all noise exposures, whether such exposures are from continuous-type noise, impulsive noise, or combined continuous-type and impulsive noises.

CHAPTER 4

Instrumentation for Noise Measurement

No single method or process exists for measuring occupational noise. Hearing safety and health professionals can use a variety of instruments to measure noise and can choose from a variety of instruments and software to analyze their measurements. The choice of a particular instrument and approach for measuring and analyzing occupational noise depends on many factors, not the least of which will be the purpose for the measurement and the environment in which the measurement will be made. In general, measurement methods should conform to the *American National Standard Measurement of Occupational Noise Exposure*, ANSI S12.19–1997 [ANSI 1996a]. However, it is beyond the scope of this document to serve as a manual for operating equipment and making sound measurements. Rather, this chapter will be limited to concise remarks relevant to operating the two most commonly used instruments for measuring noise exposures: the sound level meter and the noise dosimeter. More detailed discussions about instrumentation and measurement protocols appear in reference sources such as NIOSH [1973], Earshen [1986], Johnson et al. [1991], and Harris [1991].

4.1 Sound Level Meter

The sound level meter is the basic measuring instrument for noise exposures. It consists of a microphone, a frequency selective amplifier, and an indicator. At a minimum, it measures sound level in dB SPL. An integrating function may be included to automate the calculation of the TWA or the noise dose.

4.1.1 Frequency Weighting Networks

The human ear is not equally responsive to all frequencies; it is most sensitive around 4000 Hz and least sensitive in the low frequencies. The responses of the sound level meter are modified with frequency-weighting networks that represent some responses of the human ear. These empirically derived networks approximate the equal loudness-weighting networks or scales; some also have a B-scale. The A-scale, which approximates the ear's response to moderate-level sounds, is commonly used in measuring noise to evaluate its effect on humans and has been incorporated in many occupational noise standards. Table 4–1 shows the characteristics of these scales.

4.1.2 Exponential Time Weighting

A sound level meter's response is generally based on either a FAST or SLOW exponential averaging. FAST corresponds to a 125-millisecond (ms) time constant; SLOW

Table 4–1. Relative response of sound level meter weighting networks*

	Weighted response (dB)		
Octave-center frequency (Hz)	**A scale**	**B scale**	**C scale**
31.5	-39.4	-17.1	-3.0
63	-26.2	-9.3	-0.8
125	-16.1	-4.2	-0.2
250	-8.6	-1.3	0
500	-3.2	-0.3	0
1,000	0	0	0
2,000	1.2	-0.1	-0.2
4,000	1.0	-0.7	-0.8
8,000	-1.1	-2.9	-3.0
16,000	-6.6	-8.4	-8.5

*Adapted from ANSI [1983].

corresponds to a 1-s time constant. The meter dynamics are such that the meter will reach 63% of the final steady-state reading within one time constant. The meter indicator reflects the average SPL measured by the meter during the period selected. In most industrial settings, the meter fluctuates less when measurements are made with the SLOW response compared with the FAST response. A rapidly fluctuating sound generally yields higher maximum SPLs when measured with a FAST response. The choice of meter response depends on the type of noise being measured, the intended use of the measurements, and the specifications of any applicable standard. For typical occupational noise measurements, NIOSH recommends that the meter response on a sound level meter be set at SLOW.*

4.1.3 Microphones for Sound Level Meters

The correct use of the microphone is extremely important in obtaining accurate measurements. Microphones come in many types and sizes. A microphone is typically designed for use in a particular environment across a specific range of SPLs and frequencies. In addition, microphones differ in their directionality. For example, some are intended to be pointed directly at the sound; and others are designed to measure sound from a "grazing" angle of incidence. Thus users should follow the sound level meter manufacturer's instructions regarding the type and size of microphone and its orientation toward a sound. Also, care should be taken to avoid shielding the microphone by persons or objects [ANSI 1996a]. When measuring a diffuse sound field, the person conducting the measurement should hold the microphone as far from his or her body as practical [Earshen 1986].

---

*Meters that are set to integrate or average sound do not use either the FAST or SLOW time constant; they will sample many times each second. For a more detailed description of exponential time weighting, refer to Yeager and Marsh [1991].

4.2 Noise Dosimeter

Measuring noise with a sound level meter is relatively simple when the noise levels are continuous and when the worker remains essentially stationary during the work shift. A noise dosimeter is preferred for measuring a worker's noise exposure when the noise levels are varying or intermittent, when they contain impulsive components, or when the worker moves around frequently during the work shift.

The noise dosimeter may be thought of as a sound level meter with an additional storage and computational function. It measures and stores the sound levels during an exposure period and computes the readout as the percent dose or TWA. Many dosimeters available today can provide an output in dose or TWA using various exchange rates (e.g., 3, 4, and 5 dB), 8-hr criterion levels (e.g., 80, 84, 85, and 90 dBA), and sound measurement ranges (e.g., 80 to 130 dBA). The choice of FAST or SLOW meter response on the dosimeter does not affect the computed noise dose or TWA when the 3-dB exchange rate is used, but it will when other exchange rates are used [Earshen 1986].

In noise dosimetry, the microphone is attached on the worker whose exposure is being measured. The placement of the microphone is important in estimating the worker's exposure, as Kuhn and Guernsey [1983] have found large differences in the sound distribution about the body. ANSI [1996a] specifies that the microphone be located on the midtop of the worker's more exposed shoulder and that it be oriented approximately parallel to the plane of this shoulder.

4.3 Range of Sound Levels

OSHA requires that, for the purposes of the Hearing Conservation Amendment, all sound levels from 80 to 130 dBA be included in the noise measurements [29 CFR 1910.95(d)(2)(I)]. This range was specified on the basis of instrument capabilities available at that time [ANSI 1978], and OSHA had intended to increase the upper limit of the range to 140 or 150 dB as improved dosimeters became readily available [46 Fed. Reg. 4135 (1981b)].

To measure all sound levels from 80 to 140 dBA, a noise dosimeter should have an operating range of at least 63 dB and a pulse range of the same magnitude. In contrast, the ANSI S1.25–1991 standard specifies that dosimeters should have an operating range of at least 50 dB and a pulse range of at least 53 dB [ANSI 1991a]. Today, noise dosimeters with operating and pulse ranges in excess of 65 dB are quite common. Therefore, NIOSH considers that measuring all sound levels from 80 to 140 dBA with a noise dosimeter is technically feasible.