Safe Lifetime Occupational Noise Exposure – 1 LONE

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For many years, those working in the field of industrial noise control have struggled to educate people about how much noise will cause hearing loss over a lifetime. Part of the difficulty is a result of the logarithmic nature of decibel scaling. The concept of expressing noise exposure in industrial environments without decibels is the focus of this paper. Eldred ("Sound Exposure without Decibels," Inter-Noise 86) discusses this approach for community noise.[39] ANSI Standard S3.44-1996 defines sound exposure; the units are Pascals squared seconds, or PASQUES, as noted by Eldred. This article proposes that a safe value for lifetime occupational exposure to noise be expressed in terms of PASQUES. The authors discuss the pros and cons of such an approach and offer 11.5 million PASQUES as the upper limit for a safe lifetime exposure to occupational noise.

Hearing loss due to noise exposure in the workplace continues to be a serious health problem throughout the industrialized world. American researchers have known about noise-induced hearing loss in industry for more than 120 years. Our inability to solve this occupational-related problem is embarrassing to all involved: the government, the medical profession, industrial hygienists, audiologists, noise control engineers, and – most importantly – workers who have noise-induced hearing loss.

There are lots of special areas of understanding that make discussions of noise-induced hearing loss difficult:

- Hearing level vs. sound pressure level – a hearing level of 30 dB at 2000 Hz does not mean that you can hear a sound at a sound pressure level of 30 dB.
- Hearing protectors don't provide the noise reduction rating (NRR) listed on the box to everyone who wears them all of the time – or even some of the time.
- Hearing aids are not as good for hearing as corrective lenses are for seeing.
- Hearing aids are very expensive – five to 70 times the cost of glasses.

However, one of the biggest problems associated with noise-induced hearing loss is the problem of decibel notation. Some people can do the math in their heads, but many others find it difficult to understand and relate in a practical setting; this includes the people who need to use this information: medical doctors, safety professionals, legislators, and most importantly, the worker.

What is needed is an easier metric that conveys the same technical information without all the confusion. Would it not be easier if someone's noise exposure was discussed in units so that they can simply add the exposure at one location to that of the exposure at another location to get the total exposure? This article proposes such a metric.

Brief History

Knowledge about noise-induced hearing loss was first acquired by medical personnel, then by businesses, insurance companies, legislators, and finally by workers and their families. The following is a brief history in chronological order of knowledge and actions regarding noise-induced hearing loss. But first, a few words about noise and industry may be appropriate. In the 1940s, '50s, and '60s, many industrial plants had medical facilities on site, a service originating out of the hazardous working environment. Employing hundreds of workers, it was important for these companies to provide health care services for their employees to prevent injury, minimize damage caused by injury, and return the worker to the labor force as quickly as possible. Since medical care was often not readily available in the community, many of these facilities offered medical services for the family as well.

Unlike physical injury to the eyes, arms, hands, legs, feet, or torso, hearing loss is an injury that does not evidence itself rapidly. For example, if a worker were to get something in his/her eye, such as a particle of metal from grinding or welding, the individual would immediately have to go to the nurse or doctor. The particle would be removed from the eye, and the individual would either be sent home for the day or might return to work.

This is not the situation with hearing loss. New hires, if exposed to A-weighted sound levels greater than 80 dB, are likely to experience a temporary threshold shift – a temporary loss of hearing. The following morning, assuming their off-time has been spent in a relatively quiet environment, it is likely that the temporary loss will be gone and their hearing will be apparently restored. As a result, new hires are not aware that the repetitive noise exposure at work will give them permanent hearing loss.

Losing hearing and losing a limb are treated differently in the eyes of the medical profession. If one were to lose a finger – 10% of one's digits would be considered a serious injury. However, hearing loss is not considered serious until after the individual has lost 25 dB of hearing – or about 25% of total hearing ability!

One of the earliest references to occupational noise causing hearing loss was in 1713 when Ramazzini[1] described noise-induced hearing loss in millers and coppersmiths. He also discussed tinnitus, a condition where the individual hears ringing or buzzing in the ear without any external stimulus.

The railroad industry was particularly noisy in the days of steam locomotives, whistles, and boiler fabrication. In 1881, Gottstein and Keyser[2] reported on noise-induced hearing loss of railway workers, and in 1882, Holt[3] reported on hearing loss among boilermakers as well as his efforts to develop a device to "modify the effects of noise on the ear." Holt's paper is the first American publication linking noise exposure in the workplace to hearing loss.

In 1908, Legge reported that pneumatic tool noise caused hearing loss in workers.[4] In 1921, D. J. Gilbert published "Influence of Industrial Noises" in the *Journal of Industrial Hygiene*,[5] where he mentions a number of other papers reporting high incidence of hearing loss.

In 1936, the U.S. Congress passed the Walsh-Healey Act. It applied to companies doing business with the U.S. Government and required that working conditions not be ". . . unsanitary or hazardous or dangerous to the health and safety of employees."[6]

In 1937, C. C. Bunch presented "The Diagnosis of Occupational or Traumatic Deafness: A Historical and Audiometric Study" at the annual meeting of the American Otological Society.[7]

In 1947, MacLaren and Chaney reported on a noise and hearing-loss study at Lockheed, along with mention of their hearing conservation program.[8]

In 1949, W. E. Grove published "The Noise Hazard" in *Industrial Medicine*.[9] The author, a member of the American Academy of Ophthalmology and Otolaryngology's (AAOO) Subcommittee on Industrial Noise, covered the subjects of hazardous noise levels, noise-induced hearing loss, and protective measures. He states that industry has been slow to conserve the hearing of its workers because "it is fearful of an avalanche of medicolegal claims if the subject is stirred up." However, he believed that pre-employment audiograms, retesting of the employee's hearing a week later and at periodic intervals, and other hearing conservation measures would protect the employer as well as the employee.

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In the late 1940s and early '50s, the numerous lawsuits filed in New York and Wisconsin started a panic among industrial companies, insurance companies, and labor unions.[10] Following are simplified versions of their perspectives:

- The industrial companies reasoned, ". . . if New York doesn't want our jobs, we will go to one of the southern states where there are no unions."
- The insurance companies reasoned, "If we have to pay benefits now, it will bankrupt us."
- The unions reasoned, "If the companies move to a state without unions, we lose our support base and our members will lose rightful benefits."

The employers, insurers, and unions decided that it took six months without any exposure to noise before the hearing loss could be accurately measured. This "compromise" of scientific evidence was used to solve this conflict. In 1952, Dr. Stewart Nash summarized this settlement as follows:[11]

- The industrial plants will be kept in operation.
- The worker will have continuous employment and will not (in an effort to obtain similar work) be required to remove himself and his family to another locality.
- Deferring payment of awards until retirement will spread an otherwise ruinous expenditure over a period of years and lighten an almost unbearable financial burden on the employer and carrier.
- The worker will get his award on retirement when he needs it most.

All the professionals knew this was a compromise based on circumstances, not science.

In 1949, the U.S. Airforce issued the first noise exposure regulation. It specified limits for noise exposure in various kinds of work environments and required the provision of hearing protection devices and audiometric testing for personnel exposed to high noise levels. More detailed regulations were issued in 1956, 1960, 1973, and in later years.[12]

In 1950, Stacy Guild published "Industrial Noise and Deafness" in the *Journal of Insurance Medicine*.[13] He warned employers that they must take measures to protect the hearing of their employees if deafness and resulting disability payments were to be avoided.

In 1950, Kryter recommended a maximum safe level of 85 dB for any frequency or narrow band of noise.[14] Also, in the early 1950s, national conferences were held to discuss the problem of noise. Professionals representing all disciplines and employers attended these conferences:

- Medical personnel
- Engineers and scientists
- Industrial hygienists
- Equipment manufacturers
- Government agencies
- Corporations
- Noise control products companies
- Hearing protector manufacturers

About the same time, power, chemical, and steel companies (among others) began noise measurements and audiometric tests on employees exposed to noise.

In December 1960, the Bureau of Labor Standards issued a revision to the Walsh-Healey Act. The regulation said that noise must be reasonably controlled to reduce fatigue and the likelihood of accidents.[15]

Between 1960 and 1968, there were reports by such organizations as the Armed Forces/National Research Council Committee on Hearing and Bioacoustics (CHABA), the Intersociety Committee that consisted of representatives from the American Conference of Governmental Industrial Hygienists, the American Academy of Ophthalmology and Otolaryngology, the American Academy of Occupational Medicine, the American Industrial Hygiene Association, and the Industrial Medical Association. These organizations presented criteria that predicted hearing loss at various ages resulting from different noise levels, typically from 85 to 115 dBA.

Hearing loss due to excessive noise exposure in both the workplace and the social environment is a chronic international problem. There needs to be a simple, understandable way of expressing Lifetime Occupational Noise Exposure (LONE). The metric PASQUES (Pascals squared seconds) meets this criteria. This article presents the case for international discussion and proposed adoption as a standard.

In September of 1968, the Department of Labor proposed an 85-dBA regulation to minimize the impact of hearing loss on employees.[16] Based on Baughn's data,[17] OSHA considered that an 85-dBA exposure level would represent an excess risk of about 8% above "no-noise" risk. At 90 dBA, the excess risk would be about 17% or 18%.[18] However, when the rule was promulgated as a part of the Walsh-Healey Act that applied to all companies receiving federal contracts of more than $10,000[19] on May 29, 1969, the level was set at 90 dBA.[20] The level of 90 dBA applied to an 8-hour day, 95 dBA applied to a 4-hour exposure, 100 dBA to a 2-hour exposure, etc. (There was a 5-dBA exchange rate for every doubling or halving of the time of exposure.)

When Congress passed the Occupational Safety and Health Act of 1970, the Department of Labor extended the Walsh-Healey Act noise limits to all manufacturing firms involved in interstate commerce.[21] This provided employees with a limit on their sound level exposure that varied according to the duration of that exposure.[22] For those industries whose workers were exposed to noise levels that exceeded this limit, the act required that employers correct, if possible, the problem of excessive noise through the use of engineering or administrative controls. If these forms of control could not reduce the noise exposure or while these controls were being installed, companies should provide "a continuing, effective hearing conservation program."[23] Noise compliance programs should include noise measurement and control, audiometric testing, and hearing protection devices, among other measures.

The bulletin was issued again in 1971 as an OSHA publication. The level was set at 90 dBA instead of 85 dBA, because it was feared that the cost of compliance would be too great for industry. Note that this noise limit does not protect the hearing of all workers.

During the 1970s, OSHA continued to consider adopting an 85-dBA standard for an 8-hour exposure. However, each time that the department was close to adopting an 85-dBA standard, the anticipated cost of compliance would seem too great and the agency would stay with the 90-dBA standard.[24, 25]

Other reputable agencies advocated lower levels to protect more people. In 1971, the International Organization for Standardization[26] issued a standard with a 90-dBA criterion level for

Table 1. Summary of excess risk (40 years of exposure, 2,000 hours per year).

Average exposure level, dBA	0.5-1-2-kHz+					1-2-3-kHz+			1-2-3-4 kHz+	
	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
75	–	–	0*	–	–	–	–	–	–	–

+ These are the frequencies used to determine material impairment.

* The EPA concluded: "an 8-hour per day exposure to a 73 dB steady noise for 40 years will result in a noise-induced permanent threshold shift of no more than 5 dB at 4000 Hz."[37] The 75 dB limit is used to include all people with an adequate margin of safety.

an 8-hour exposure (based on a 40-hour work week) and a 3-dBA exchange rate instead of the 5-dBA exchange rate used by OSHA. The standard has been used in many European countries. The risk of incurring impaired hearing (hearing handicap) from a 40-year exposure to 90 dBA was estimated at 21%.

In 1972, NIOSH recommended a permissible exposure limit of 85 dBA and presented detailed requirements for different hearing conservation programs.[27] In 1973, the EPA published its report detailing the risk of noise-induced hearing loss from long-term average exposures of 75, 80, 85, and 90 dBA. The EPA estimated the risk of hearing handicap from a lifetime's exposure to 90 dBA to be 22%.[28]

In 1974, the EPA identified an average level of 70 dBA as the sound level to protect the entire population from even the smallest amount of hearing loss. This sound level translates to an 8-hour (occupational) level of 75 dB(A).[29]

In 1981 and 1983, OSHA amended the noise regulation. The impact was to clarify precisely what was meant by a "continuing, effective hearing conservation program" as spelled out in OSHA's regulation[30, 31] and to require that hearing protection be made available to employees exposed to sound levels greater than 85 dBA.

In 1998, NIOSH presented its revised thoughts on occupational hearing loss.[32] Table 1 presents the comparisons of excess risk due to noise based on a number of definitions of material impairment and sound level exposures. NIOSH recommended an 85-dBA limit for 8 hours of exposure and recommended using a 3-dB exchange rate rather than the 5-dB exchange rate used by OSHA.

The following organizations have sent letters to the OSHA encouraging the modification of the OSHA regulation by reducing the exchange rate from 5 dB to 3 dB and to reducing the PEL (permissible exposure level) for an 8-hour exposure from an A-weighted sound level of 90 dB to that of 85 dB:

- Industrial Safety Equipment Association
- American Association of Occupational Health Nurses
- American Society of Safety Engineers
- American Industrial Hygiene Association
- International Institute of Noise Control Engineers
- National Hearing Conservation Association

The lead author of this paper has served as chair of a subcommittee on the control of hazardous noise for the National Academy of Engineering as part of the NAE's Technology for a Quieter America project. NAE's report was published in 2010 and contains recommendations with respect to OSHA policy regarding hazardous noise in the workplace as well as information on engineering controls and "buy quiet" programs (www.nap.edu/openbook.php?record_id=12928&page=31).

In October 2010, OSHA announced that it intended to interpret "feasible" as "capable of being done." In January 2011, OSHA withdrew this interpretation from consideration.

In summary, from 1882 to the present, medical doctors, corporations, and insurance companies have been learning about noise-induced hearing loss. Unfortunately, workers are not as informed. A review of magazine articles from 1890 to 1990 mentioning noise (excluding aircraft and airport noise) was conducted. Of the 829 articles, only 28 were in magazines likely to be read by workers (*Popular Mechanics*, *Popular Science*, *Outdoor Life*, *Field & Stream*, *Mechanix Illustrated*, *Guns and Ammo,* etc.). Of these 28, only two presented the important information of how a worker could know how noise damages hearing.[33]

Sound Exposure

The time-weighted average or the equivalent sound level, both using A-weighting and measured in dB, are today's attempt to communicate sound exposure. Of course, with such a number, one has to say that it is the 8- or 12-hour sound exposure. Another approach is to try and calculate the OSHA noise dose, but this is also pretty useless, since it relates only to compliance with the OSHA regulation and not to preventing noise-induced hearing loss in all workers.

ANSI Standard Definition. ANSI Standard, S3.44–1996,[34] defines sound exposure as the square of the sound pressure in Pascals times the length of the exposure in seconds. The square of the sound pressure can be determined from Equation 1.

$$p_{\text{exp}}^{\ 2} = 10^{(Lp/10)} * p_{ref}^{\ 2} \quad (1)$$

where:

$p_{exp}^{\ 2}$ = square of exposure sound pressure
$p_{\text{ref}}^{\ 2}$ = square of exposure sound pressure 20 μPa
L_p = A-weighted sound pressure level

The sound exposure is determined by equation 2.

$$\text{Sound exposure} = (p_{\text{exp}}^{\ 2}) \times (\text{length of exposure in seconds}) \quad (2)$$

The units of sound exposure are Pascals squared seconds or PASQUES. Table 2 presents the sound exposure in PASQUES for 1-second exposures to different sound levels.

Safe Sound Level. To calculate the safe sound exposure, it is necessary to identify the sound level that does not cause "hearing loss" above the "acceptable" 25 dB of hearing loss used as the "fence." Candidates for this A-weighted sound level:

- 70 dB, for 24-hour exposure (adequate margin of safety for people not developing 5 dB of hearing loss)
- 75 dB, for 8-hour exposure[35] (adequate margin of safety for people not developing 5 dB of hearing loss)
- 80 dB, "no increase in risk"[36] for developing hearing handicap (25 dB hearing loss)
- 85 dB, ~8% risk of developing hearing handicap
- 90 dB, ~18% risk of developing hearing handicap

Of these possibilities only the top three have the potential to meet the concept of a safe noise exposure. The 80-dB level was recognized for many years as "no increase in risk" for noise contribution to hearing loss. However, Table 1 illustrates that the risk is more likely 3% than 0. EPA looked closely at the need to hear high-frequency sounds such as fricatives and stop consonants as shown in Figure 1. For these sounds, hearing loss above 3,000 Hz

Table 2. Sound exposures for one second, in decibels and PASQUES.

Sound Level, dB	Sound Exposure, PASQUES
80	0.04
85	0.13
90	0.40
95	1.26
100	4.00

Table 3. Sound exposures for a working lifetime.

Years	Days/ year	Hours/ day	Total Hours	Total Seconds	Equiv. A-weighted Sound Level, dB 75	80
40	250	8	80,000	288,000,000	3,642,944	11,520,000

Table 4. Length of time to reach 1 LONE without hearing protection.

A-Weighted Sound Level	Time/year to reach 1 LONE in 40 yrs
80	2000 hrs
85	632 hrs
90	200 hrs
95	63 hrs
100	20 hrs
105	6 hrs
110	2 hrs
115	0.6 hrs (38 minutes)

Table 5. Allowable time for each of 500 events.

A-Weighted Sound Level	Time of Each Event
80	160 hr
85	51 hr
90	16 hr
95	5 hr
100	1.6 hr
105	30 min
110	10 min
115	3 min

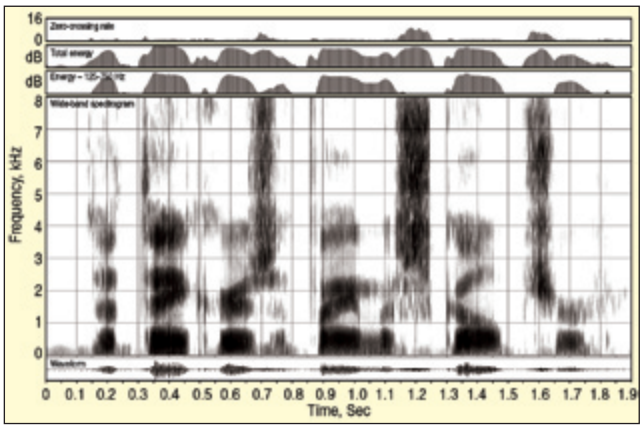

Figure 1. MIT example of speech showing fricatives and stop consonants.[38]

can degrade understanding of speech, and this is why EPA recommended 75 dB for an 8-hour exposure.

Length of Exposure. It is generally understood that the hearing loss from noise exposures was based on an assumed working lifetime that consisted of 250 days at 8 hours per day, or 2,000 hours of annual exposure to work noise with a working lifetime of 40 years. This represents 80,000 hours of noise exposure or 288,000,000 seconds.

Safe Sound Exposure. The sound exposures in PASQUES for a working lifetime of 80,000 hours are shown in Table 3 for sound exposures of 75 and 80 dB. Thus, a safe sound exposure for all workers would be something between 3.6 and 11.5 million PASQUES. To protect all people from 5 dB of hearing loss, the 75 dB alternative would be the proper scientific decision. However, economics may make this unrealistic in the short term. The authors recommend the adoption of 11.5 million PASQUES as a safe noise exposure for a worker's lifetime – a lifetime occupational noise exposure, or 1 LONE. At this exposure level, there would be an excess risk of hearing loss of about 3%; wearing hearing protection would thus protect all exposed workers from hearing loss.

Table 4 presents a summary showing how quickly allowable sound exposure accumulates. The table assumes that a person works 8 hours per day for 40 years. In the left-hand column, the A-weighted sound level is presented. The right column presents the length of time per year that it takes to reach 11,520,000 PASQUES in a lifetime. So for an 80-dBA environment, the length of time is 2,000 hours – 250 days at 8 hours per day. As the sound level increases, the length of time grows dramatically shorter. Listening to music via headphones at A-weighted sound levels of 85-90 dB for more than 2 hours a day is likely to produce hearing loss in 40 years!

Table 5 presents comparable calculations for personal events such as loud concerts, races, etc. The calculations are based on an allowance of 500 events in a lifetime, with each event allowed 0.2% of the LONE. The-left hand column is the A-weighted sound level, and the right column is the length of time that each of the 500 events can last.

Future Considerations. The length of the workweek for those employed in industry continues to change, depending on occupation, country, union presence, overtime policies, leave policies, and a myriad of other factors. Changing the exposure time from 2,000 hrs per year, will change the number of years required to accumulate the 11.5 million PASQUES.

Conclusions

Noise exposure of workers in industry should be expressed in PASQUES to facilitate the easy calculation of the lifetime occupational noise exposure. The proposed lifetime occupational noise exposure (1 LONE) is 11,500,000 PASQUES.

Acknowledgements

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