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Exposure limits for airborne sound of very high frequency and ultrasonic frequency

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ABSTRACT

This document considers the subjective and auditory effects of audible sound in the very high frequency range (10-20 kHz) and also in the inaudible ultrasonic range (greater than 20 kHz). A number of Damage Risk Criteria and Maximum Permissible Levels were first recommended by individual researchers in the 1960s. These provisional recommendations, supported by limited experimental and survey data, were then adopted by national and international bodies. The exposure limits were published with the intent of avoiding any subjective effects and any auditory effects, in any exposed individuals. At present, the exposure limits lack the sophistication to predict hearing damage and adverse subjective effects caused by sounds outside the customary frequency range for occupational noise exposure assessments.

KEY WORDS

Damage Risk Criteria, Maximum Permissible Levels, ultrasound, subjective effects, hearing damage, hearing loss, temporary threshold shift

LIST OF ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
dB	decibels
DRC	Damage Risk Criterion
ILO	International Labour Office
INRC	International Non-Ionizing Radiation Committee
MPL	Maximum Permissible Level
SPL	Sound Pressure Level, dB re 20 micropascals
TTS	temporary threshold shift
VHF	very high frequency
WHO	World Health Organzation

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1. INTRODUCTION

During the 1960s, hearing Damage Risk Criteria were proposed for noise exposures involving very high frequencies (VHFs, 10-20 kilohertz) and extending into the ultrasonic frequency range (greater than 20 kHz, considered to be the upper frequency limit of young normal hearing). These Damage Risk Criteria (DRCs) or Maximum Permissible Levels (MPLs) appear to have been put forward without extensive research on dose-response relationships, to control the risk of hearing loss due to occupational noise not adequately quantified by A-weighted Sound Level. The present paper summarises the historical background of the DRCs from the 1960s, and considers how this topic has developed during the intervening decades. Comments are offered on whether our knowledge has advanced to allow improvement, or at least confirmation, of the existing limits.

Searches were made of the English-language acoustical, medical, occupational hygiene and industrial safety literature, seeking information on hearing damage or dysfunction, and subjective reaction caused by airborne sound with components outside the customary frequency range for the assessment of occupational noise. Exclusive use of English-language sources is not a serious shortcoming. German, Scandinavian and Japanese authors frequently publish in English to reach an international audience. Russian work is often translated for publication in reputable English-language journals. Research reports, case studies and DRCs were critically reviewed elsewhere (Lawton, 2001); summary conclusions are offered here, relating to subjective and auditory effects that might result from exposure to VHF and ultrasonic noise.

2. STATEMENT OF NOISE LIMITS FROM AROUND THE WORLD

There are several ultrasound DRCs first recommended by research organisations and individuals. Soviet, UK and American research from the 1950s and 60s set the scene with a reasoned approach, supported by limited experimental and survey data. Table 1 lists MPLs given by individual researchers as one-third-octave band Sound Pressure Levels (SPL, decibels re 20 μPa); their work is summarised in the paragraphs below. Any noise with a component exceeding one or more of the band limits was deemed hazardous to some degree by the research workers in question.

PARRACK (1966)

Parrack gave an account of press reports on “ultrasonic sickness” in US Air Force ground crew working within a few metres of jet engines. To counteract the “speculative publicity”, research was undertaken to provide facts on the effects of airborne ultrasound. Parrack gave a description of work done in 1950, to determine the effect of VHFs and ultrasound on human hearing.

Audible tones ranging from 9.2 kHz to 15 kHz were presented to individual listeners for five minutes at SPLs between 140 dB and 156 dB. These stimuli produced Temporary Threshold Shifts (TTS) at frequencies half an octave higher than the signal frequency, as expected. TTS was also observed one octave below the signal frequency; these shifts, usually less than 20 dB, recovered rapidly.

Tones of 17, 21, 24, 26 and 37 kHz were presented to individual listeners for five minutes at SPLs in the range 148 to 154 dB. Hearing threshold shifts, usually less than 20 dB, were observed at lower frequencies 8.5, 11, 12, 13, 15 and 18.5 kHz; recovery of pre-test hearing sensitivity at or near these sub-harmonic frequencies was rapid and complete.

On the basis of these results, Parrack advised that industrial or environmental sound fields in the ultrasonic frequency range should be harmless to the human ear unless octave band or one-third-octave band levels approached 140 dB. In 1969, Parrack reduced his recommended band limits to those given in Table 1; the citations by the World Health Organization (1982) and by Acton (1983) refer to private communications.

GRIGOR'EVA (1966)

Experiments were conducted at the All-Union Central Scientific Research Institute of Occupational Hygiene in Moscow to contrast the physiological effects of tones in the ultrasonic and audible regions. Subjects were exposed for an hour to a tone of 20 kHz at 110 dB. Tests were made to determine hearing threshold shifts over the frequency range 250 Hz to 10 kHz. Heart rate, body temperature and skin temperature were also monitored. All of these tests showed no appreciable effect, even when the SPL was increased to 115 dB. These same subjects were given a one-hour exposure to a 5 kHz tone at 90 dB: a considerable TTS was found.

These results indicated that airborne ultrasound is considerably less hazardous than audible sound. A limit of 120 dB was proposed for airborne ultrasound of frequency 20 kHz or higher. Further TTS experiments were performed to determine acceptable Sound Pressure Levels for high-frequency tones in the audible region. From these further results, Grigor'eva suggested the following limits, without reference to any specified duration:

one-third-octave band centre frequency (kHz)	6.3	8	10	12.5	16
Sound Pressure Level (dB)	75	80	85	90	90

These band limits were intended to avoid the possibility of TTS: a sound that does not produce temporary dullness of hearing cannot produce a permanent noise-induced hearing loss.

ACTON (1968)

During the 1960s, Acton was exploring the possibility of hearing damage by the noise of industrial ultrasonic equipment. He accumulated a number of spectra from industrial tools and appliances showing ultrasonic components in their one-third-octave analyses, along with reports of (or absence of) subjective effects experienced by the users.

MPLs were proposed on the basis of possible hearing damage risk, and the presence or absence of subjective effects for measured spectra. If band levels were below 75 dB for the one-third-octave bands centred at 8, 10, 12 and 16 kHz, then no subjective effects would be expected. Symptoms including nausea, fullness in the ears, tinnitus and persistent headaches would be avoided. A tentative extrapolation of DRCs (current at the time) suggested that 8 hour exposures to levels of 110 dB in the 20 kHz, 25 kHz and 31.5 kHz bands would not result in hearing loss in the audible frequencies.

This work by Acton gives a clear statement of the dual-aim limit. Audible VHF sounds were found to produce unpleasant, even alarming, subjective effects. Russian and American work showed the potential of auditory harm from possibly inaudible ultrasonic noise. To prevent both insult and injury, different limit levels were needed for the two frequency regimes.

ACTON (1975)

After Acton's first proposal, a shortcoming of the 1968 criteria came to light. The original proposal set a limit of 110 dB for the 20 kHz one-third-octave band, with nominal band-edge frequencies of 17.6 and 22.5 kHz. The lower end of this frequency range is within the audible range for a significant proportion of the population, especially young females. At 110 dB, such VHF sounds would be expected to cause severe subjective effects. Therefore, Acton revised his recommendation down to 75 dB for the 20 kHz band.

ACCEPTANCE OF THE RECOMMENDED LIMITS

These first interim limits were taken up by national and international bodies, and repeated with enough regularity over several decades to gain a degree of authority and permanence, perhaps not deserved. Table 2 lists the international manifestations of the limits.

Since the proposal of these limits, there have been no reports showing systematic hearing loss trends associated with occupational exposure to VHFor ultrasonic noise. A review of the scant literature (Lawton, 2001) showed few workers represented, and none with more than about five years of daily contact with potentially harmful VHF or ultrasonic noise. Workday exposure conditions are not described sufficiently to judge if any recognised limit had been exceeded.

3. INTERPRETATION OF EXISTING OR PROPOSED BAND LIMITS

For audible sounds with frequencies up to and including the 20 kHz band, the proposed limits of Tables 1 and 2 cover a relatively narrow range (disregarding the ceiling values of the ACGIH, 2004). Typically, values of 80 dB were set to avoid unpleasant subjective effects. It is instructive to compare this typical level with thresholds for such sounds heard by young, normal listeners (in the age range 18-33). Table 3 gives such thresholds for VHF tones heard by quasi-free-field presentation at azimuth angle 0° for binaural listening. The bottom row of the Table gives the maximum difference, limit minus threshold, as Sensation Level in dB. For young persons, unpleasant subjective effects would be expected for sounds of relatively modest Sensation Levels. For older persons, with a degree of age-associated hearing loss in these high frequencies, the typical limit value of 80 dB would seem somewhat quieter, or not be heard at all at some frequencies.

4. SOME FURTHER ASPECTS

HEALTH CANADA (1991)

This Canadian government document presents a review of the health effects expected from occupational exposure to ultrasound. With high-power industrial tools or appliances, the objective is to expose the workpiece to vibratory energy of sufficient magnitude to bring about permanent physical change in the material; an example might be welding. The main hazard to the tool user is energy input to the body by accidental contact with the tool head, or any fluid containing ultrasonic energy. However, many industrial or commercial devices also release airborne energy, giving high SPLs in both the audible and ultrasonic frequency ranges. This incidental sound can produce both physiological and hearing effects.

For airborne ultrasound at levels greater than approximately 155 dB, acute harmful effects will occur in exposed persons, primarily as a result of sound absorption and subsequent heating. It was deemed plausible that lengthy exposure to such high levels might raise body temperature to mild fever levels during the exposure periods. However, such high SPLs had never been encountered in either commercial or industrial applications.

MPLs were set out for airborne ultrasound. For the one-third-octave bands centred at 16 and 20 kHz, the limit was set at 75 dB; for the bands at 25 to 50 kHz, the limit was 110 dB. These band limits are independent of duration as subjective effects may occur immediately.

AMERICAN CONFERENCE OF GOVERNMENTAL INDUSTRIAL HYGIENISTS (2004)

Table 2 shows that the American industrial hygiene ceiling values for ultrasound are somewhat higher than limits from other nations or bodies. These more permissive limit values are said to "represent conditions under which it is believed that nearly all workers may be repeatedly exposed without adverse effect on their ability to hear and understand normal speech." The implication is that such high levels (for seconds, minutes or hours per day over many working years) would not produce socially-significant hearing losses over the frequencies 0.5 to 4 kHz, generally considered to carry the majority of speech information.

A line of reasoning is offered: previous ACGIH limits for the frequencies 10 to 20 kHz were set to prevent subjective effects. In some individuals, annoyance and discomfort might occur at levels between 75 and 105 dB for the frequencies from 10 kHz to 20 kHz, especially if the sounds were tonal in nature. For the frequency bands 25 kHz and higher, the source document gives ceiling values (typically 115 dB) that may be raised by 30 dB when there is no possibility that the ultrasound can couple with the human body by touching water or some other transmission medium. These higher values are reported in Table 2. This reviewer suspects that the ceiling values, 140-145 dB, are linked to the report of Parrack (1966): ultrasonic tones at slightly higher levels were shown to produce TTS.

The ACGIH limit values seem intended to avoid TTS that, if repeated on a regular basis, might develop into a permanent and significant noise-induced hearing loss. The striking difference between the ACGIH limits and all others suggests that the ACGIH has pushed its exposure limits close to the edge of potentially injurious exposure.

5. THE INFLUENCE OF DURATION

INTERNATIONAL LABOUR OFFICE (1977)

The ILO recommended that maximum SPLs near workplace sources of ultrasound should not exceed 75 dB in the one-third-octave band centred at 12.5 kHz, 85 dB in the 16 kHz band, and 110 dB for the bands at 20 kHz and higher. For any total duration of ultrasound not exceeding 4 hours per day, these levels might be relaxed as follows:

duration 1 to 4 hours	6 dB permitted increase
15 minutes to 1 hour	12 dB
5 to 15 minutes	18 dB
1 to 5 minutes	24 dB

These increases for reduced time are intended to represent the "equal energy hypothesis": two sounds with identical amounts of acoustic energy represent the same risk to hearing. For a constant degree of risk, halving or doubling the duration of any sound should be offset by a change of level, +3 dB or -3 dB respectively, for constant acoustic energy. The supplements from the ILO do not follow the equal energy line exactly, but sawtooth about it, sometimes more lenient, sometimes more stringent.

Almost as a footnote, a valuable insight is offered concerning the occupational environment. In practice, the audible high frequencies that frequently accompany ultrasound are sufficient to cause the effects attributed to ultrasound. Such VHF noise, in the range 10 to 20 kHz, may be a problem for young persons, while these components may not be audible to the (older) supervisors who have the responsibility for noise control.

It is also worth asking: is the incidence of unpleasant subjective effects related solely to the level of a VHF sound, or does duration play a part? In addition to its occupational aspects, this question also has significance when considering ultrasonic vermin-repellers, intruder alarms, and VHF devices intended to disperse unwanted gatherings outside commercial premises. One may justifiably wonder if subjective effects would appear in susceptible individuals after only a few minutes of a VHF noise at a level deemed "safe" according to the equal energy concept.

INTERNATIONAL NON-IONIZING RADIATION COMMITTEE (1984)

This organisation's band limits for occupational exposure to VHF sound and airborne ultrasound may be seen in Table 2; the limits apply to continuous exposure of workers for an 8 hour working day. For shorter durations, the permissible levels may be increased:

duration 2 to 4 hours per day	3 dB permitted increase
1 to 2 hours	+6 dB
less than 1 hour	+9 dB

As seen before, these supplements for reduced time represent the "equal energy hypothesis", with a halving or doubling the duration of any sound opposed by a change of level, +3 dB or -3 dB respectively, for constant acoustic energy. These supplements from the INRC do not follow the equal energy line exactly, but sawtooth below it. The permitted increases are conservative.

6. CONCLUSIONS

From the evolution of MPLs as seen here, it is plain that the limiting level for the very high frequencies, up to 20 kHz, was set low, at 75-85 dB, to avoid unpleasant subjective effects in young workers. For older workers, age-associated hearing loss would cause the 75-85 dB range to be perceived at quite a low loudness, if audible at all. For ultrasonic components, MPLs in the range 105-115 dB were established to avoid the possibility of hearing damage in the much lower audible frequencies. Save for the ACGIH limits: the American limits are noticeably more permissive, with higher limit values at all frequencies. These higher levels indicate an acceptance that subjective effects are not harmful, and will not produce any decrement in communication ability. The higher acceptable levels may also be linked to the American view (which may or may not be held currently) that some degree of hearing loss is tolerable in a working population.

There is also a range of views on the influence of time, as it is related to exposure dose. None of the MPLs seen here have a fully-developed Exposure Level, calculated from the variables SPL and noise duration. Where duration is considered at all, there is a trading relationship broadly in line with equal-energy considerations. Any alteration of limit, to account for duration, is a basic feature of schemes to assess the hearing damage potential of occupational noise. However, the band limits set out by researchers and governmental bodies have two stated aims: to avoid subjective effects and to avoid hearing loss, either temporary or permanent. In sensitive individual workers, unpleasant subjective effects might be expected to appear almost as soon as VHF or ultrasonic noise exposure begins. An increase of permitted band level, in line with a daily duration correction, may be expected to hasten the onset of adverse subjective effects in sensitive individuals, and possibly to involve a larger proportion of the exposed population. Any duration supplement works to thwart one stated aim of the limit.

Do the various MPLs indicate a degree of intended protection, that is, what percent of the exposed population is protected against what degree of hearing loss? On this point, most of the limits reviewed here are quite plain: the Maximum Permissible Levels are set to avoid *any* subjective effects and *any* auditory effects.

When considering hearing damage by noise, the concept of intended protection is quite sophisticated, requiring knowledge of the noise dose (level and duration) required to produce a hearing damage response over the range of susceptible individuals. With knowledge of how all of the various factors interact, one may predict what proportion of an exposed population would suffer a specified degree of hearing loss from a known exposure. For conventional broadband occupational noise as might be experienced in any number of workplaces, the idea of intended protection may be applied, as long as one is prepared to grapple with the troublesome social concept of the boundary between tolerable and unacceptable noise-induced hearing loss. As far as sound of very high frequency or ultrasonic frequency is concerned, the dose-response relation is unknown: most limiting levels have been set low, deliberately to avoid any effect whatever.

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Table 1
Maximum Permissible Levels for VHFs and airborne ultrasound, recommended by research groups or individuals

one-third-octave band centre frequency (kHz)	8	10	12.5	16	20	25	31.5	40	50	wide-band ≥ 20 kHz
source:	band Sound Pressure Level (dB)									
Grigor'eva (1966)	80	85	90	90	–	–	–	–	–	120
Acton (1968)	75	75	75	75	110	110	110	–	–	
Parrack, 1969 cited in WHO (1982) and Acton (1983)	–	80	80	80	105	110	115	115	115	
Acton (1975, 1976)	75	75	75	75	75	110	110	110	–	

Table 2
Maximum Permissible Levels for VHFs and airborne ultrasound, set out by organisations or national governments

one-third-octave band centre frequency (kHz)	8	10	12.5	16	20	25	31.5	40	50
source:	band Sound Pressure Level (dB)								
Internat. Lab. Off. (1977)	—	—	75	85	110	110	110	110	110
cited in Lee (1980)									
ACGIH, 1979		80	80	80	105	110	115	115	115
WHO (1982)									
Japan, 1971	90	90	90	90	110	110	110	110	110
USSR, 1975	—	—	75	85	110	110	110	110	110
US Air Force, 1976	—	—	85	85	85	85	85	85	—
Sweden, 1978	—	—	—	—	105	110	115	115	115
Canada, 1980	80	80	80	80	80	110	110	110	110
INRC IRPA (1984)									
occupational exposure	—	—	—	—	75	110	110	110	110
general public	—	—	—	—	70	100	100	100	100
cited in Damongeot, André (1985)									
Norway, 1978	—	—	—	—	—	——120 (octave)——			
Australia, 1981	—	75	75	75	75	110	110	110	110
cited in Tanttari (1986)									
USSR, 1983	—	—	80	90	100	105	110	110	110
Health Canada (1991)	—	—	—	75	75	110	110	110	110
ACGIH (2004)									
8 hour average	—	88	89	92	94	—	—	—	—
ceiling values	—	105	105	105	105	140	145	145	145
cited in Pawlaczyk-Łuszczyńska *et al.* (2007)									
Poland, 2002									
L_{eq8h}	—	80	80	80	90	105	110	110	—
L_{max}	—	100	100	100	110	125	130	130	—
US Department of Defence (2010)	—	80	80	80	105	110	115	115	115

Table 3
Sensation Levels (dB above threshold for free-field, frontal incidence pure tones) for typical limit values within the frequency range of the human auditory system

tone freq. (kHz)	8	10	12.5	16	20
one-third-octave limit, typical value (dB SPL)	80	80	80	80	105
thresholds from:	tone threshold (dB SPL)				
Henry, Fast (1984)					
mean 20 males,18-20 yrs	16.7	25.1	*21.2*	44.8	91.0
mean 26 females, 18-20 yrs	18.9	23.0	*24.3*	44.4	91.4
mean 15 males, 21-24 yrs	21.4	24.9	*26.1*	49.8	95.0
mean 11 females, 21-24 yrs	21.1	26.0	*26.3*	50.1	93.0
Takeshima *et al*. (1994)					
median, 18+ subjects, 19-25 yrs	9.4	11.8	10.6	50.5	
Poulsen, Han (2000)					
median 31 subjects, 18-25 yrs	12.3	16.0	16.8	42.7	
Takeshima *et al*. (2001)					
mean 32 subjects, 18-25 yrs	11.2	15.4	14.7	44.5	
Kurakata *et al*. (2003)					
median 51 subjects, 18-24 yrs	10.4	13.9	*10.2*	41.4	
Kurakata *et al*. (2005)					
median 46 subjects, 18-24 yrs	9.3	10.8	11.5	36.4	
BS EN ISO 389-7:2005	12.6	13.9	12.3	40.2	
greatest Sensation Level (dB)	71	69	*70*	44	14

values in *italics*
for a tone of 12 kHz