A SIMPLE OUTDOOR CRITERION FOR ASSESSMENT OF LOW FREQUENCY NOISE EMISSION

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INTRODUCTION

Complaints about the effect of higher level Low Frequency Noise (LFN) in the form of rumble, a "feeling of pressure" and resultant headaches and nausea have been known for decades [1,2]. Human hearing becomes gradually less sensitive as frequency decreases, so for humans to perceive LFN, that is, to perceive frequencies below 100 Hz, the sound pressure level must be relatively high when compared to that for mid frequency noise, e.g. 500–3000 Hz. As the frequency decreases toward the infrasonic range (frequencies less than 20 Hz and a subset of LFN), the sensation of hearing changes to one of a feeling of ear pressure and envelopment for those noises which exceed the hearing threshold.

It can be said that the effects of LFN are broadly similar to those of high frequency noise in the sense that any unwanted sound is potentially annoying. However, LFN exhibits itself in the form of "rumble" and "pressure" and while not at all loud in the normal sense of the word, LFN can exacerbate the annoyance reaction when compared to higher frequency noise, especially when the noise is perceived to be "fluctuating" or "throbbing".

An example of a possible LFN problem case is shown in Figure 1 below which presents the linear narrow band Sound Pressure Level (SPL) spectrum in the bedroom of a house adjacent to a gold mine with two vibrating screens operating. The wife of the house owner complained about a "rumble" noise causing her sleep disturbance and she was the only person in the house to hear the "noise'. Figure 2 below shows the A-weighted one-third octave band spectrum in the bedroom of the house while the screens were operating. The tone at the 16 Hz third octave can be readily seen.

Figure 3 presents the overall sound pressure level versus time trace in the bedroom with both of the screens operating. The modulation effect is clearly observable and can be seen to begin once the screens start operating. The modulation period is approximately 60 seconds. A waterfall plot showing sound pressure level versus frequency versus time in the third dimension is shown in Figure 4. The variation in level in the 16 Hz third octave band (due to the tone at 16.48 Hz) can be seen by the change in colour representing level. The periodic level variation at this frequency is from 58 dB down to 29 dB. It could be understood from these plots that such a LFN might cause some form of annoyance to anyone that might hear or perceive it.

For this case, the overall A-weighted SPL was 19 dBA, the overall dBC fluctuated from 49 dBC to 36 dBC while the overall linear SPL varied from 57 dBZ to 43 dBZ. The (C-A) level difference indoors varied from 30 dB down to 17 dB.

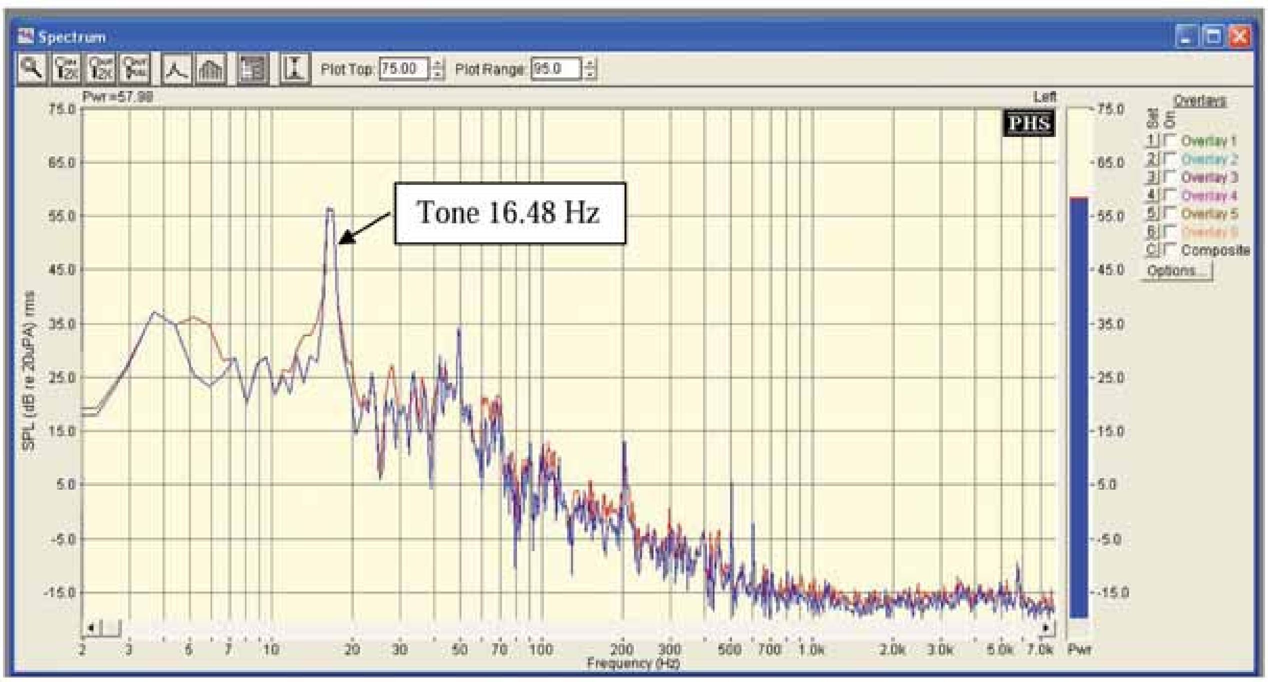

Figure 1. Narrow band spectrum in bedroom of house near a gold mine when the screens are in operation

Figure 2. A-weighted third octave band spectrum in bedroom of house near a gold mine when the screens are in operation

However, as can be seen in Figure 5, the maximum spectrum is well below the ISO median hearing threshold level [3]. Even if it is considered that at 125 Hz, 10% of 60 year old males have a better hearing sensitivity than the median 18 year old by 4 dB and that 2% are more than 12 dB more sensitive (see [3]), it can be seen that it is very unlikely that, in this instance, the complainant can actually perceive the sound as claimed.

Indeed, the complainant claimed to be able to hear the "rumble" even when the screens were not operational, so that this further raises doubt as to what the complainant was actually "hearing" or "perceiving". The extremely low level of background noise in the bedroom was noted and it was wondered whether in this instance, a lack of masking noise is responsible for the apparent claim. The observed screen level fluctuations would appear to possibly be just co-incidental in this case.

TYPICAL LOW FREQUENCY NOISE SOURCES

There are many sources of LFN in the environment [4]. These range from boilers, pumps, fans, cooling towers, ventilation plant and gas turbines to wind farm turbines [5,6]. At larger distances from many industrial plants, the noise character will be that of LFN due to the relatively large attenuation of high frequency energy as compared to LFN (note that the LFN level also decreases due to geometrical spreading). Transportation noise sources such as aircraft and diesel trains also are sources of LFN. Helicopters generate LFN and blade slap in particular. Furthermore, LFN can be generated at pubs/band venues and concerts where the bass sound is considered as wanted sound by patrons but can be very annoying to neighbours.

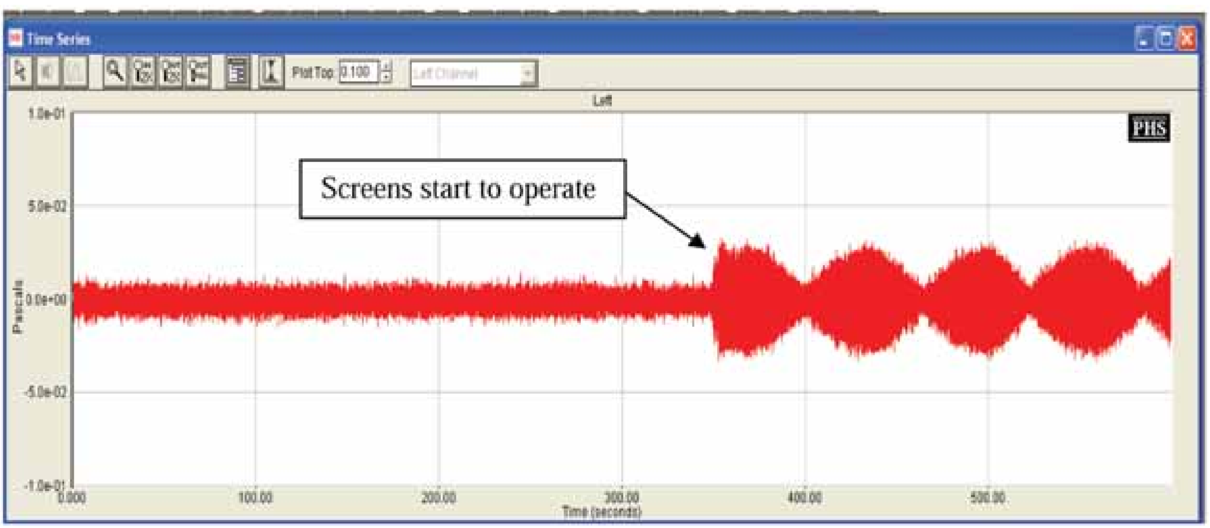

Figure 3. Sound pressure level versus time plot in bedroom of house near a gold mine when the screens are in operation

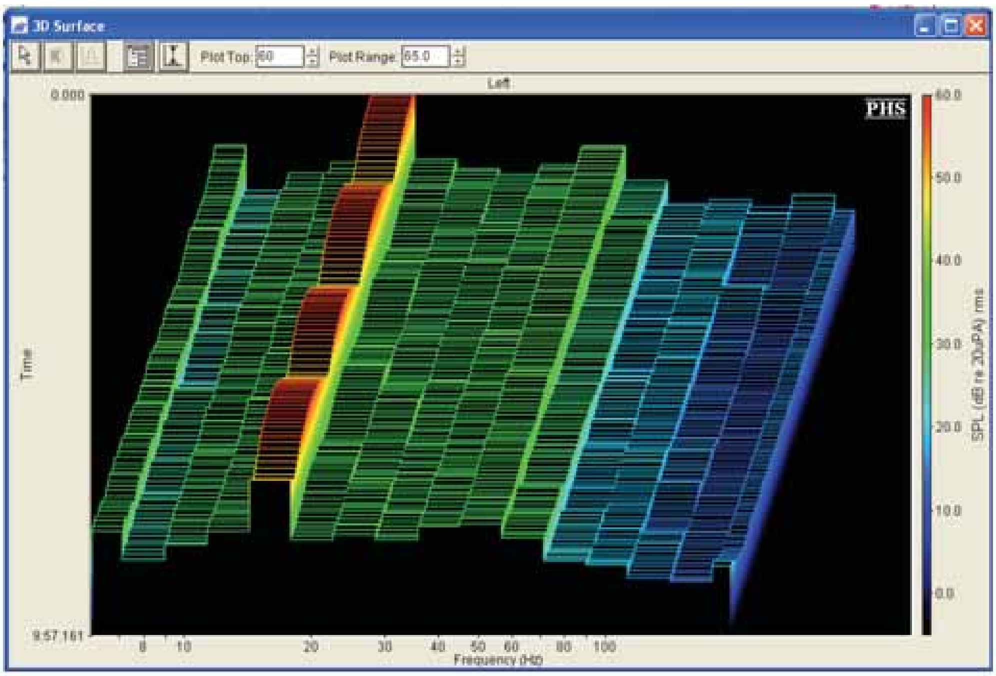

Figure 4. Third octave sound pressure level versus frequency vs time plot in bedroom of house near a gold mine when the screens are in operation

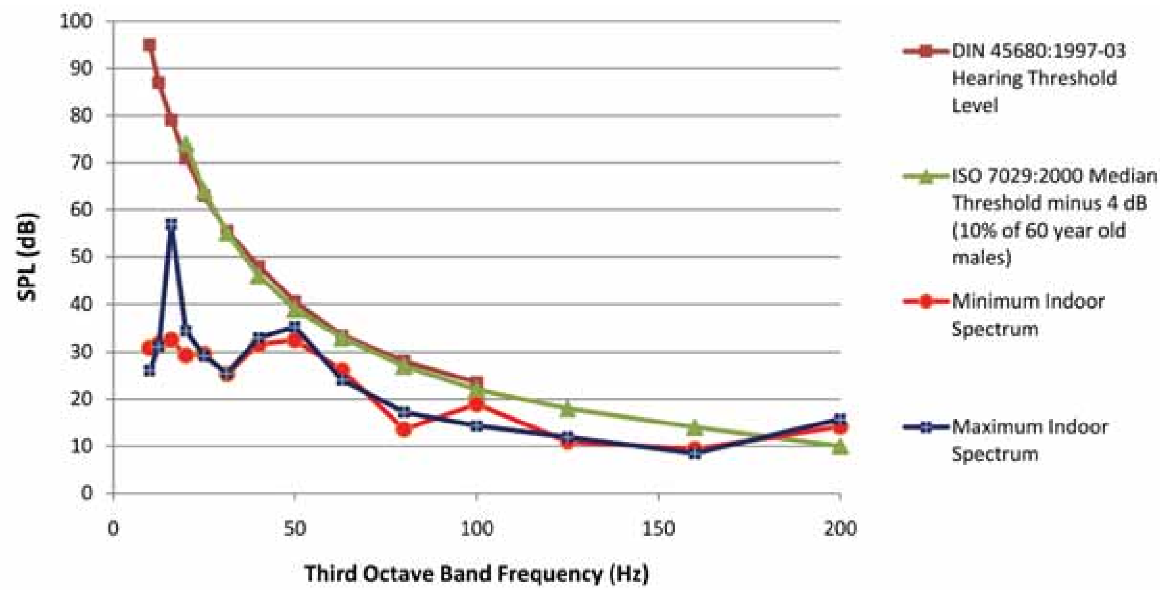

Figure 5. Maximum and minimum third octave sound pressure level in bedroom of house near a gold mine when the screens are in operation versus the threshold of hearing

Typical low frequency noise sources include:

- Open cycle gas turbines
- Boilers
- Forced draft and induced draft fans
- Shakers on hoppers
- Vibratory screens
- Compressors
- Wind farms

The noise sources listed above generate low frequency noise due to the operation of various items of plant or equipment in the following sites:

- **Power Station** - Open Cycle Gas Turbines / Forced Draft Fans generate low frequency due to combustion and turbulent air flow.
- **Industrial Sites** - Boilers generate low frequency noise through combustion noise / Forced Draft Fans generate turbulent airflow
- **Mine Sites / Quarries** - Shakers on hoppers / vibratory screens generate low frequency noise due to excitation of the structure, large FD/ID fans associated with exhaust stacks may generate LFN.
- **Wind Farms** – Wind Turbine Generators with the rotors downwind of the tower were noted for LFN due to the

passage of the blades through the tower's wind shadow (resulting in pulses at about one per second which were analysed as infrasound). However, current generation wind turbines have the rotors "upwind" of the turbine tower thus avoiding this problem. Turbine blade rotation may result in a "swishing" sound which is at higher frequencies with a low frequency modulation. This should not be confused with LFN though some LFN may result from a wind farm of many wind turbines under some meteorological conditions [7].

It should be realised that just because these sources exist at a site, it does not necessarily mean that a LFN problem will occur. There are many plants/facilities with LFN sources in them and where LFN is not a problem in the surrounding community. Whether or not LFN becomes a problem will depend on the level of the LFN, whether it is fluctuating and on other individual circumstances.

LFN PERCEPTION AND ASSESSMENT

Perception and Annoyance

Based on empirical and laboratory studies, it can be shown that the primary effect due to LFN appears to be annoyance and that this affect is greater than would be expected based on the A-weighted level alone [5, 6, 8-10]. It would seem that for sound with "tonal" low frequency content below 50 Hz and for infrasound (< 20 Hz), particularly where the sound level is perceptibly fluctuating or throbbing, annoyance and loudness are perceptually treated differently and that this difference may increase with time [11]. As the loudness adapts more rapidly with time than the annoyance (i.e. the perceived loudness decreases more rapidly with time than the perceived annoyance), the effect is to effectively increase the annoyance with time. Hence it seems that we can adapt to the loudness element more readily than to the annoyance. This effect would be more pronounced for lower frequency infrasound where, at levels above the hearing threshold, the sound is not so much heard but is rather perceived as a feeling and sensation of pressure. The perception of annoyance is particularly dependent on the degree of amplitude modulation and spectral balance [12-14]. As a result, it is considered that there is a significant limitation in the long term averaging of LFN noise levels, as this approach results in the loss of information on fluctuations [2, 10, 15].

Applicable Noise Measures

Assessment and prediction of annoyance due to LFN is not simple. Based on empirical evidence and many documented cases [2, 10, 16], it is very clear is that the A-weighted SPL alone is not successful in assessing the response to LFN (and to infrasound). One obvious reason for this is that the A-weighting network significantly decreases the contribution of low frequency energy in a sound due to the reduced loudness sensitivity of a person's hearing at low frequencies. The relative response for the A-weighting is shown (in blue) in Figure 6. It can be seen that the A weighting network significantly reduces the contribution to the sound of the low frequencies. At 250 Hz, the reduction is -9 dB and at 63 Hz, the reduction is -26 dB.

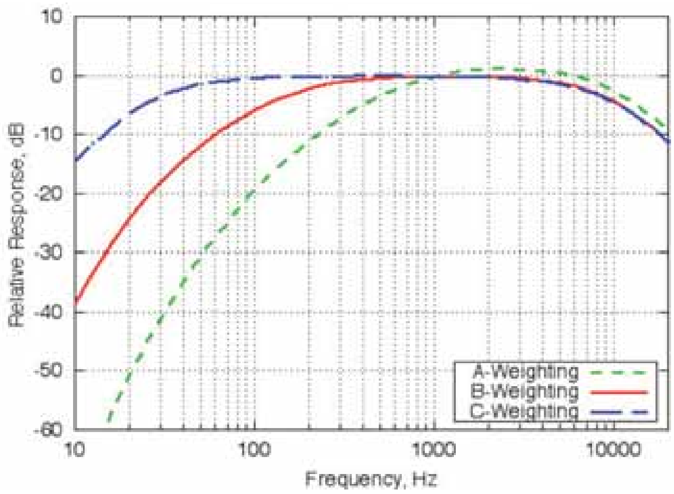

Figure 6. The A, B and C weighting networks [17]

Although the A-weighting network is commonly used for most applications, the 'C' weighting is more appropriately used for assessment of higher noise level generating noise sources and for some entertainment noise level measurements (see the blue line in Figure 6). This is because at higher sound pressure levels (SPLs), that is at approximately 100 dB, the ear's response is flatter than at lower SPLs and this response is represented by the 'C'-weighting. The C-weighting includes nearly all of the low frequency energy in a signal and so would be more appropriate for situations where the transmission of bass noise or significantly high levels of LFN from plants or equipment can be a problem in the community. As a comparison, at 250 Hz, the C-weighting is zero and at 63 Hz, the weighting is only -0.8 dB. In addition, because until recently there was no accepted Standard for the Linear network, if one wanted to use a noise measure that didn't significantly affect the low frequency content of a signal when they were measuring it, the C-weighting network would have to have been chosen.

It can be deduced from the above discussion that a simple method of indicating how much LFN there is in a sound would be to subtract the A-weighted SPL from the C-weighted SPL. Both the A and C weighted SPLs are readily available on current sound level meters so it easy to determine this difference quite readily. It could be expected that the (C-A) difference might be a reasonably good indicator of the presence of LFN which could cause annoyance. But there are two questions viz. what (C-A) difference is necessary, and, is this difference the same at all sound levels? Note that all of the A, C and Z weighting networks are currently defined [18].

Assessment based on (C-A)

As indicated above, the (C-A) difference can provide an indication of how much LFN is present in a sound. Empirical evidence shows that where the imbalance is such that the difference between the Linear and A-weighted Sound Pressure Levels is at least 25 dB, the sound is likely to cause annoyance. Broner and Leventhall [10] and DIN 45680-1997 [19] suggested that a difference of 20 dB can result in an unbalanced spectrum which could lead to LFN annoyance. Similarly, the Alberta EUB [20] requires the (C-A) difference to exceed 20 dB to determine the presence of a LFN problem. Others have suggested that a difference of only 15 dB was a good rule of thumb to identify a potential infrasound LFN problem situation [21]. In New South Wales (Australia), the current Industrial Noise Policy (INP) [22] allows the determination of either an intrusiveness or amenity criterion when considering land use planning. It recommends that a 5 dB modifying factor be added to the outdoor A-weighted measured/predicted sound pressure level when the 'C' weighted sound pressure level minus the 'A' weighted sound pressure level difference is 15 dB or greater.

Based on the above, it is recommended that a minimum (C-A) difference of at least 20 dB is necessary to indicate the possible presence of a LFN problem. However, a greater difference may be permissible at low A-weighted levels, as the (C-A) difference for low levels of background noise may exceed 20-25 dB without causing complaints

In general, the (C–A) level difference is only an appropriate starting metric for indicating when a potential LFN problem may become a significant source of annoyance to the public. As indicated previously, averaging the SPL to obtain the difference can lead to loss of information in terms of fluctuations and spectral balance and modulation also needs to be considered. The predictive ability of the (C-A) difference is therefore of limited value (see also [2]) and indeed, as can be seen from the above, higher (C-A) differences are suggested as being necessary to indicate a LFN problem. What would be most suitable is a simple overall criterion below which annoyance due to LFN is not expected to occur regardless of the (C-A) difference (or above which annoyance could be anticipated). In addition, if it is necessary to utilise a (C-A) SPL difference at all, it is recommended that a (C-A) difference of at least 20 dB be used to indicate the presence of a potential LFN noise problem. A review of overall noise level criteria for LFN is presented in the following section which will assist in determining if a complaint due to LFN should be considered.

OUTDOOR LOW FREQUENCY NOISE LEVEL ASSESSMENT

It has been known for many decades that gas turbines, boilers, forced draft fans and other sources can produce low frequency noise which can cause feelings of annoyance due to nausea, headache and uneasiness and vibration induced rattle. In terms of simplicity of application, the determination of an overall noise level that could be used for assessment of LFN would be the optimum approach rather than requiring any detailed spectrum analysis and calculations (as are required in some European countries – see above). Much of the data concerning an acceptable external overall criterion for LFN comes from research associated with power station noise. However, any criteria so developed would certainly apply to any LFN problem regardless of the source due to the spectral and fluctuating characteristic of the consequent LFN.

Concern about the impact of LFN on residential communities was already raised by Hoover in 1973 [23] who recognised that, if homes were located within 1000 feet of an open cycle gas turbine (OCGT) installation, then the SPL in the 31.5 Hz octave band needed to be no more than 65–75 dB at 400 feet. Hoover suggested a guideline that the SPL in the 31.5 Hz octave band should never exceed 70 dB (L_{eq} 67 dBC) or even 65 dB (L_{eq} 62 dBC) outside a house when ambient levels were in the range 48–53 dB.

ANSI B133.8 -1977 [24] recognised that for installations where frame structures are occupied by people near to gas turbine installations, the A-weighted sound level alone does not adequately define permissible low frequency sound emissions. Indeed, ANSI B133.8 Appendix B recommends the selection of a maximum C-weighted level outside the nearest occupied framed structure and suggests the upper limit should be selected not to exceed 75–80 dBC. The range of values was given due to uncertainty as to the sound level required to induce a structural vibration in a frame structure.

Challis and Challis [25] also recognised that even though a level of 40 dBA might seem to be moderate, gas turbine emissions could have SPLs as high as 96 dB at 16 Hz and 110 dB at 10 Hz which are both audible, causing strong negative community response. Challis and Challis [25] also identified a number of English and Australian Utilities that had specified criteria, basically NR curves, but with significantly reduced noise levels below 63 Hz, specifically for 8Hz, 16 Hz and 31.5 Hz Octave Bands. These utilities had experienced LFN problems and came up with their criteria for neighbouring residences based on the experience of others. As an example, Figure 7 shows the specification for two utilities for stack emission at 100 metres [25]. These two criteria are quite different and vary from L_{eq} 72 dBC to L_{eq} 60 dBC.

In discussing low frequency gas turbine noise, Newman and McEwan [26] quoted a British Gas Corporation criterion for specifying noise control for gas turbines viz. 60 dB in the 31.5 Hz octave band at the nearest dwelling. This would be equivalent to L_{eq} 57 dBC. This value was said to have been determined by review of the noise levels which complainants found satisfactory.

In 2001, Hessler [27] noted that low frequency noise was only a problem for OCGT plants and he recommended that "a level of 70 dBC at the closest residence is normally low enough to prevent perceptible vibration but that a slightly lower level of 65 dBC is needed in quiet, rural environments where the residual ambient noise level is low". In 2005, Hessler [28, 29] described the low frequency noise problems that have occurred in the USA due to incorrect siting of gas turbine power plants close to residential areas. Typically, neighbours expressed complaints of low frequency rumble noise, vibration rattle, nausea and headaches in some people. At low frequencies, apart from the spectral imbalance issue, a major factor in causing annoyance is the significant temporal level fluctuations that may occur. Hessler considered that his experience since 1971 had shown that the recommendation of ANSI B133.8 was "woefully inadequate" for protecting residential areas against low frequency noise problems and that the problem continued to occur for combustion turbine open cycle plants. He therefore proposed C-weighted SPLs supplementary to the A-weighted site criteria which are listed in Table 1. These levels contained no factor of safety or

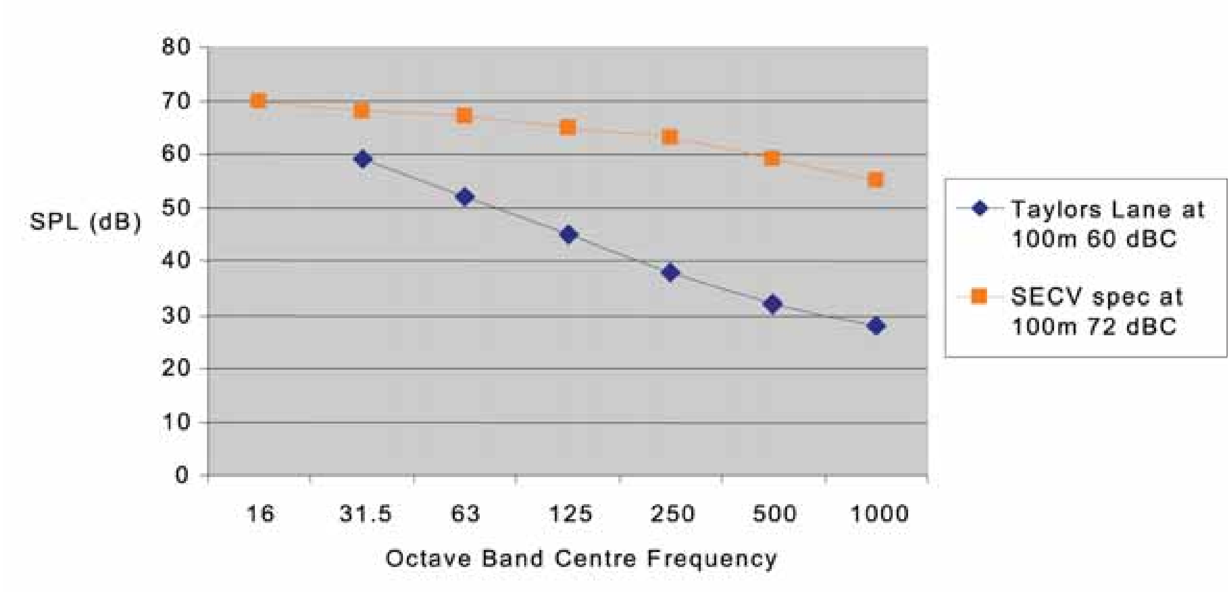

Figure 7. LFN specifications by utilities quoted by Challis and Challis [25]

margin of error and Hessler cautioned that these levels should be considered the maximum allowable. Hessler [30] has since clarified that his criteria are all in terms of the C-weighted L_{eq}.

Table 1. Maximum allowable dBC levels at residential areas to minimise infrasound noise and vibration problems

	For normal suburban/ urban residential areas, daytime residual level, L_{90}>40dBA	For very quiet suburban or rural residential areas, daytime residual level, L_{90}<40dBA
For intermittent daytime only or seasonal source operation	70	65
Extensive or 24/7 source operation	65	60

Similarly, Annex D of ANSI S12.9 – 2005/Part 4 [31] deals with sounds with strong low frequency content and for essentially continuous sound where the C-weighted sound level exceeds the A-weighted sound level by at least 10 dB. Annex D provides a means for calculating an adjustment to the sound exposure level based on the summation of the time–mean–square sound pressures in the 16, 31.5 and 63 Hz octave bands. ANSI recognises that generally, annoyance is minimal when octave band sound pressure levels are less than 65 dB at these octave bands (equivalent to L_{eq} 67 dBC) and that to prevent the likelihood of noise-induced rattles, the low frequency sound pressure level should be less than 70 dB (ANSI does not make clear which octave bands this applies to but it is presumably at the 16, 31.5 and 63 Hz octave bands – this would be equivalent to L_{eq} 72 dBC).

The Oregon State Noise Control Regulations [32] for industrial and commercial noise sources also quote low frequency allowable octave band sound pressure levels for the 31.5 Hz and 63 Hz octave bands as 65 dB and 62 dB respectively for the night time period 10pm – 7am [this would be equivalent to L_{eq} 65 dBC] (the limits are 68 dB and 65 dB for the daytime period 7am – 10pm respectively [equivalent to L_{eq} 68 dBC]).

Table 2. Summary of outdoor criteria for LFN

Developed by	Citeria
Hoover	67 dBC (70 dB at 31.5 Hz) should never be exceeded
Challis	72 dBC overall with 70 dB @ 16 Hz 60 dBC overall with 60 dB @ 31.5 Hz
ANSI B133.8 1977	75-80 dBC
Hessler	Max 70 dBC when L_{90} >40dBA daytime intermittent, normal suburban, Max 65 dBC when L_{90} >40dBA 24/7, normal suburban Max 65 dBC when L_{90} <40dBA daytime intermittent, quiet suburban, Max 60 dBC when L_{90} <40dBA 24/7, quiet suburban
Newman	57 dBC - 6 dB @ 31.5 Hz
ANSI S12.9	67 dBC to minimise annoyance 72 dBC to prevent noise induced rattles
Oregon USA	65 dBC between 10pm-7am 68 dBC between 7am-10pm
Hale	65 dBC
Hessler	65 dBC with a maximum regulatory limit of 70 dBC (wind turbines)

In a recent paper, Hale [33] described a power plant that was to be located in an area where the proposed project location was in an unincorporated jurisdiction that had enacted C-weighted daytime and night time noise limits of 50 dBC and 45 dBC respectively. In response to objections by both commissioners and the local community, the original power plant location was abandoned and a new site selected. The project sought and obtained a noise variance for a 65 dBC noise limit at the plant boundary. The local consultant indicated that the C-weighted SPLs due to the plant did not comply because of 16 Hz tones. However, the local community indicated the operating plant could not be heard in the community and Hale concluded that the plant design was adequate for compliance with the noise variance limit and that no noise impacts to sensitive locations would occur.

In a very recent paper dealing with wind turbines, Hessler and Hessler [34] recommended a limit of 65 dBC with a maximum regulatory limit if 70 dBC but also cautioned that a C-weighted SPL limit does not mix well with wind turbine applications because it is extremely difficult to accurately measure C - weighted sound levels in the presence of any kind of wind. Table 2 summarizes the outdoor noise level criteria for LFN.

RESIDENTIAL CRITERIA VS COMMERCIAL CRITERIA

It is clear from the above that:

- High levels of LFN are necessary for perception.
- Most cases of LFN annoyance occur when an unbalanced spectrum occurs with a decreasing level as frequency increases.
- LFN needs to be above threshold for a nuisance to occur but there is a very small percentage of the population that may be more sensitive to LFN than most ie they have relatively low LFN thresholds and tolerance.
- Continuous audible LFN can be a noise nuisance in the same way as can be any other noise.

Ideally, LFN criteria should be set for indoors where the LFN complaints normally occur. However, in planning terms, it is much easier to set criteria for the outside of residences where artefacts of the measurement do not play such a big role and where there is no need to enter a person's premises after start-up to confirm compliance with an outdoors noise level specification. Similarly, an overall noise level criterion is much preferred to one relying on an octave band or third-octave band analysis and calculation. We would therefore propose that to prevent low frequency noise complaints, the simplest approach is to limit the overall noise level outside the residential locations to the following:

For the daytime or when the LFN source operates only intermittently (for 1 - 2 hours):
Desirable: L_{eq} 65 dBC
Maximum: L_{eq} 70 dBC.

For the night time or for where the LFN operates continuously (24/7), it is proposed that the criteria for residential locations should be:
Desirable: L_{eq} 60 dBC
Maximum: L_{eq} 65 dBC.

The impact of LFN level fluctuations also needs to be considered as when they occur, the annoyance is exacerbated due to the significant change in perceived loudness with change in SPL at LFN. Thus, if the dBC level is fluctuating at least +/- 5 dBC (ie 10 dBC overall fluctuation), the above criteria should be reduced by 5 dBC.

Should there be a different set of criteria for commercial office/industrial locations? For commercial office/industrial situations, there would appear to be an expectation that acceptable LFN noise levels could be higher than for residential areas. In most circumstances, office/commercial structures are much more solid than a framed residential house. In addition, it could be expected that there would be greater tolerance to low frequency noise from LFN sources such as OCGT peaking plants, if these plants are operated for only short time periods during the normal working day or after normal working hours when employees are not normally present. On the other hand, LFN due to incorrectly balanced HVAC systems may be continuous, but not necessarily at as high a SPL. Thus, for day operations or where the LFN source only operates intermittently (say 1-2 hours), it is proposed that the criteria for offices/commercial structures should be:
Desirable: L_{eq} 75 dBC
Maximum: L_{eq} 80 dBC

For night time operation or for where the LFN operates continuously (24/7), it is proposed that the criteria for offices/commercial structures should be:
Desirable: L_{eq} 70 dBC
Maximum: L_{eq} 75 dBC

Again, a "penalty' of 5 dBC to the proposed criteria is recommended where the measured LFN SPL is fluctuating at least +/- 5 dBC. The above criteria are expected to protect 90-95% of the population. There will always be someone who might be more sensitive than the majority of the population. In such a circumstance, a detailed investigation by an acoustic consultant who is familiar with LFN problems might be warranted. On the other hand, an exceedance of the recommended criteria by 2-3 dBC should not necessarily result in LFN complaints if the noise source is not continuous.

RECOMMENDATION

Ideally, LFN criteria should be set for indoors where the LFN complaints normally occur. However, for the purpose of planning, it is much easier to set criteria for outside residences. Based on a review of many case histories and the literature, the author recommends the criteria listed in Table 3.

Table 3. Criteria for assessment of LFN

Sensitive Receiver		Range	CriteriaL_{eq} (dBC)
Residential	Night time or plant operation 24/7	Desirable	60
		Maximum	65
	Daytime or Intermittent (1-2 hours)	Desirable	65
		Maximum	70
Commercial/ Office/ Industrial	Night time or plant operation 24/7	Desirable	70
		Maximum	75
	Daytime or Intermittent (1-2 hours)	Desirable	75
		Maximum	80

If the measured LFN SPL is fluctuating at least +/- 5 dBC, then a "penalty' of 5 dBC to the proposed criterion (ie a reduction in the proposed limit) is recommended. When measuring the noise, all energy down to 10 Hz should be considered (the weightings are not defined for frequencies less than the 10 Hz one-third-octave-band and, in addition, do not generally contribute significantly to the overall SPL). Further, a minimum sampling duration of 3-5 minutes should be used so as not to average out the LFN fluctuations which are characteristic of many LFN problems. This is further to ensure that the low frequency sound level is sampled accurately.

The noise levels to be recorded are the maximum and minimum C-weighted SPLs using the Fast time weighting, the L_{C10} and L_{C90} levels (the C weighted SPL's exceeded for 10% and 90% of the recording time) for the purpose of providing an indication of the level fluctuation of the LFN. The same metrics are to be recorded using the A-weighting instead of the C-weighting.

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