

INCORPORATING LOW FREQUENCY NOISE LEGISLATION FOR THE ENERGY INDUSTRY IN ALBERTA, CANADA

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ABSTRACT

Environmental noise from energy industry facilities in Alberta, Canada, is regulated by the province's Energy Resources Conservation Board (ERCB) (until 2008 known as the Alberta Energy and Utilities Board [EUB]) as set out in *Directive 038: Noise Control*. The 2007 edition of the directive, which comprises a comprehensive policy and guide, adopts A-weighted energy equivalent sound levels (L_{Aeq}), with sound pressure level criteria, as the primary measurement system for a receptor location. With the receptor being some distance from the energy industry noise source, the high and medium frequency components can dissipate or be absorbed by air and ground conditions, leaving mostly low frequency noise (LFN). Consequently, A-weighted measurements do not reflect the full annoyance potential of the remaining industrial noise. Complaints related to LFN are often described by the affected party as a deep, heavy sound, like "humming," sometimes with an accompanying vibration. In some cases, the direction of the source of the LFN will be unknown to the receptor. However, it is the complainant that is most able to detect the presence of the LFN, signifying a particular sensitivity of the individual to the sound while others in the same family may not be able to detect the sound at all. To make a proper determination for the presence of LFN, the data must be collected during a time when environmental conditions are representative of when the sound is annoying. Residents who are impacted by LFN may suffer from sleep disturbances, headaches, and in some cases chronic fatigue. This paper examines the work undertaken by the ERCB to understand the issue, the various metrics tested to easily identify LFN, and finally the approach that would be incorporated into the new 2007 edition of *Directive 038: Noise Control* to address the problem.

1. INTRODUCTION

As the lead regulator for the energy industry in Alberta (oil and gas exploration, production and transportation, refineries, oil sands, coal mines, select chemical plants, and electrical generation and transmission, including wind turbines), the Energy

Resources Conservation Board (ERCB) (until 2008 known as the Energy and Utilities Board [EUB]) has a tremendous responsibility to ensure that Alberta's resources are developed in the public interest, of which environmental noise is a key component. The ERCB first became aware of low frequency noise (LFN) as a potential problem area in the early 1990s. At that time, there seemed to be a growing disconnect between the level of annoyance expressed by some residents and the measured nighttime sound levels taken at their dwellings in an A-weighted level equivalent (L_{Aeq}).

The ERCB (formally EUB) *Directive 038: Noise Control* uses an A-weighted energy equivalent (L_{Aeq}) to measure energy industry facility sound levels [1]. These sound level readings are compared to the permissible sound level (PSL) established for a residence and can determine if the facility noise level is in compliance with the ERCB requirements. A major part of the *Noise Control* directive's success is the use of a noise impact assessment (NIA) at the design stage of an application. An NIA predicts sound levels from the proposed facility at the nearest or most impacted residence [1]. Industry must complete an NIA prior to application submission for any new permanent facilities having a continuous noise source or for modifications to existing permanent facilities. The ERCB believes that by completing an NIA, the licensees consider possible noise impacts before a facility is constructed or in operation. In fact, *Directive 038* suggests that a facility be designed 5 decibels (dB) (L_{Aeq}) below the PSL to account for worst-case situations, possible LFN, and inability of noise mitigation measures to meet performance levels [1].

Although A-weighting best approximates human hearing, it tends to discount the presence of LFN [2]. The ERCB was in agreement with the University of Salford's (2005) range for LFN, noise levels typically below 250 Hz, especially when an industrial noise source is a significant distance (i.e., more than 1000 m) from nearby residences [2]. In most cases, the ERCB found that a nighttime sound level of 40 dB L_{Aeq} or less at a resident's home should not create any significant annoyance levels as these outdoor sound levels would result in acceptable indoor noise conditions [3]. However, some A-weighted sound pressure level measurements from noise sources (such as industrial facilities) measured at a resident's home did not correlate with expected annoyance levels [3]. Difficulties arise when a resident has excessive annoyance due to LFN, yet the industrial source is in compliance with the *Noise Control* directive based on the L_{Aeq} results. In rare cases (less than 10% of complaints), annoyance expressed by residents were not consistent with the norm and an analysis of 1/3 octave band data pointed to higher than expected LFN levels. These results became problematic; while the A-weighted (L_{Aeq}) value did not exceed the PSL requirements and was in compliance with the *Noise Control* directive, it did contain a significant LFN component, which was the major source of annoyance for the residents [3].

It was clear that the ERCB needed to find a way to easily identify when LFN might exist, measure it appropriately, and modify the L_{Aeq} somehow to properly and equitably account for the LFN being produced. To accomplish this, the ERCB took a three-phased approach. The first phase was to undertake a literature review on the human health and annoyance effects of LFN. The second phase was to identify all the potential metrics

that could be used to quantify LFN, and then conduct field testing to see which of these worked best for the ERCB relative to its legislative mandate and general approach to regulatory procedure. The third phase was to examine what other jurisdictions (local and worldwide) were doing to solve issues associated with LFN.

2. RESEARCH CONSIDERATIONS FOR ERCB LEGISLATION

Before any research could be conducted and relevant information gathered, the scope of the project had to be defined. *Directive 038: Noise Control* applies to industrial energy facilities throughout Alberta and contains environmental standards to which these facilities must adhere regarding industrial noise. The *Noise Control* directive was designed to ensure minimal annoyance within communities and the environment [1]. Therefore, the methods that needed to be researched had to apply to the far field where, on average, there is a 6 dBA loss per doubling of distance for a point source [4]. ERCB research was undertaken with the primary objective to quantify the impacts of LFN on humans and find the best way to measure it.

- ◆ The metric selected for LFN analysis would need to be performed with current equipment used by industry and acoustical consulting engineers. Any methodology that would require significant additional equipment and expense to meet the regulatory requirements would not be acceptable.
- ◆ The LFN measurement methodology would need to dovetail into the existing measurement criteria so that the basic fundamental metrics (L_{Aeq}) of *Directive 038: Noise Control* would remain intact. In compliance testing, this would likely result in some sort of adjustment factor (if LFN were determined to be present) that would be added to the industrial facility's comprehensive sound level (CSL) and then compared to the PSL.
- ◆ The new analysis techniques would need to be easily understood by all users of *Directive 038: Noise Control*, including not only acoustical experts but also laypersons from industry and the public. Moreover, the application of the techniques would need to be simple to ensure that there would be no mistaking the application of LFN concern for an industrial facility.

3. LITERATURE REVIEW ON THE IMPACTS OF LFN

Over the years, it seemed that the ERCB would always have several noise complaints that proved to be very difficult to resolve. In all these cases, the measured nighttime comprehensive sound levels (L_{Aeq}) were below the required permissible sound level for the industrial facility. Psychoacoustic research on annoyance, presented by Berglund and Lindvall (1995), found that L_{Aeq} values close to 40 dBA (nighttime) should not be an issue for the resident [5]. Additional assessment of the ERCB's monitoring results usually found a higher than normal LFN influence, including a strong tonal component. It became clear to the ERCB that there needed to be a much better understanding of why LFN was occurring and what impacts it was having on nearby residences.

The LFN research that followed consisted primarily of literature searches, which revealed an extensive array of impacts and concerns with regard to human health. The overall fundamental characteristic of LFN is that of “intrusiveness” [6]. Research conducted by Lindberg and Backteman (1988) found that LFN contributes to annoyance responses by

- creating a sensation of pressure in the ear,
- periodically masking effects on medium to high frequency sound with a strong modulation effect that can disturb normal conversation, and
- by creating secondary vibrating effects typically experienced within homes [7].

In addition, Berglund and Lindvall (1995) documented a number of potential behavioural dysfunctions associated with LFN, such as

- task performance deterioration,
- reduced wakefulness, and
- sleep disturbance, headaches, and irritation [5].

It has also been learnt that LFN does not need to be considered “loud” for it to cause such forms of annoyance and irritation [6]. For instance, when a low frequency component that measures 50 dB at 50 Hz on the linear scale (dB) is translated to the A-weighted dBA scale, it measures 20 dBA and will have little effect on augmenting the L_{Aeq} level [8]. In fact, LFN is found to be more difficult to ignore than higher frequency noise, and sufferers describe it as

- omnipresent,
- impossible to ignore,
- worse indoors (due to the effects of vibration),
- impossible to locate, and
- difficult to tune out [6].

Unlike higher frequency noise issues, LFN is very difficult to suppress. Closing doors and windows in an attempt to diminish the effects sometimes makes it worse because of the propagation characteristics and the low-pass filtering effect of structures [6]. Individuals often become irrational and anxious as attempts to control LFN fail, serving only to increase the individual’s awareness of the noise, accelerating the above symptoms.

Research conducted by Broner and Leventhall (1985) also showed quite a significant difference between genders in their response to loudness [9]. Their experiments demonstrated that males tend to react to loudness with a significantly higher response than females [9]. The annoyance response remains similar between genders; although males seem to be more sensitive to high noise levels and middle-aged females had a higher sensitivity to low noise levels [9]. All of the above symptoms, annoyances, and differences between genders were consistent with ERCB noise complaint files for residents affected by LFN.

4. MEASUREMENT METHODOLOGIES

The ERCB's literature review validated that there were very real and significant impacts related to LFN exposure. The ERCB was also convinced that the measurement requirements detailed in the 1999 edition of the *Noise Control* directive were not effective in identifying the presence of LFN or in making industry aware that such a problem existed. Consequently, the next step was to research the most effective ways to measure LFN while keeping in mind the need to use current monitoring equipment and the need for any new requirements to dovetail into existing ones. Below are the highlights of what was learnt from published reports and subsequent field trials.

4.1) A-Weighting

The A-weighted decibel scale is represented by dB(A), or dBA. The L_{eq} is the average A-weighted sound level over a specified period of time [1]. All sound weighting methods were developed in an attempt to measure sound signals in a similar fashion to human hearing mechanisms [10]. All of the different weighting techniques compress sound from a broad range of frequencies into a sound pressure level (SPL) at the middle frequency (1000 Hz) [11]. The A-weighting evaluation method was specifically developed to mimic the human response to broadband sound levels [4]. However, when a measured sound spectrum has LFN tonal components between 20 and 250 Hz, the A-weighted L_{eq} (L_{Aeq}) measurements disproportionately remove the low frequency sound energy [10]. In addition, A-weighting methods are level dependent, so their accuracy depends on the SPL (a direct measure in decibels of the variation in air pressure) [4]. Another significant flaw prevalent in A-weighted SPL is that it does not account for the effects of mutual masking among the components in a complex sound, because it is measured with the linear weighting and only measures the acoustic pressure without any adjustment for human ear sensitivity [12].

It is clear that when a sound is dominated by LFN, an alternative measurement method to A-weighting is required. Unfortunately, there are only a limited number of weighting scales that have the potential to address this problem specifically. The ERCB recognizes that the health and annoyance effects stemming from LFN is a real concern to the residents of rural Alberta and should be dealt with in a timely manner. However, it also acknowledges that A-weighting is still a common sound measurement tool and must still be applied to current and near future regulations.

4.2) C-Weighting

The C-weighting measurement method is comparable to the A-weighting method, except C-weighting does not de-emphasize low frequency sound energy (20 to 250 Hz) to the same extent that A-weighting does [4]. On its own, C-weighting is somewhat efficient for assessing LFN because its linear weighting system does not try to mimic the means in which a human perceives sound; it weighs all frequencies equally [4] (with the exception of infrasound, which is less than 20 Hz, and ultrasound, which is 8000 Hz and higher) [13].

Due to this property, C-weighted measurements can be used alongside A-weighted SPLs to determine the existence of LFN [14]. The method of subtracting the C-weighted sound level equivalent (L_{Ceq}) from the L_{Aeq} has been adopted throughout Europe to quantify LFN more efficiently, but Europe uses this method more in building regulations than in the free field assessment [15]. The general rule of thumb in European countries, such as Sweden, is that if the difference between the L_{Ceq} and L_{Aeq} measurement is greater than 15 dB, an LFN assessment is required [16]. However, this magnitude of difference between weighted values on its own hardly identifies if an LFN problem exists. The high slope of the hearing threshold towards lower frequencies might mean that the low frequencies may be below normal human ear thresholds, so the problem may not exist [17].

The ERCB took the European standard for addressing LFN and adopted it to meet the needs of the energy industry here in Alberta, Canada. The requirements put in place by the ERCB for addressing LFN are discussed in the *Alternative Measurement Techniques* section of this paper.

4.3) Other Weighting Scales

Although the A- and C-weighted SPLs are used most by acousticians today, other weighting scales do exist. B-weighting was developed specifically to mimic the human response to moderate sound levels [18]. This is not a common weighting network, but could possibly be the best weighting scale to account for LFN within the free field. It does not delete low frequency energy levels to the extent that A-weighting does, but its relative response to low frequencies is still less than that of C-weighting [18]. B-weighting has undergone very little research and virtually little to no equipment exists that could measure L_{Beq} values.

D-weighting was specifically developed for noise around airports [19]. D-weighting does not de-emphasize much low frequency energy and boosts the high frequency range between 1000 and 12 000 Hz [19]. This weighting network has been researched but has not been adopted by any international standards group [19]. Moreover, a similar scale, G-weighting, was specifically designed as an infrasonic noise (0 to 20 Hz) evaluation index [20], but again would be too difficult to incorporate into current legislation.

J-weighting was introduced to deal with LFN and annoyance aspects. Characteristics of J-weighting include a correction factor for impulsiveness and a weighting shape similar to pre-existing loudness curves (when using broad-band compared to single-tone signals), except for frequencies around 50 Hz that are depressed with respect to the higher frequencies above 125 Hz [21]. J-weighting appears to be only effective in dealing with low to moderate annoyance levels and, unfortunately, only gives a value slightly below the A-weighting scale. J-weighting would therefore be too small of a drop to integrate as a new standalone frequency weighting [21].

4.4) Loudness

A great deal is known about the human hearing process and how it takes place within the ear. What is not well understood is the relationship between the measured physical SPL and the subjective way in which people relate to the sound [22]. It is widely understood that an acoustic signal of a specific SPL is perceived to be of a different volume by humans than an acoustic signal of the same SPL at a different frequency. This phenomenon led to extensive testing by Moller and Watanabe (1990) of large groups of people with normal hearing in the 18- to 25-year age group to establish how loud or soft a sound was of pure tones at different frequencies with changing SPLs relative to a standard 1000 Hz tone [23]. From these tests, equal loudness level contours were developed that have been referenced in a number of international standards [23].

The equal loudness level contours are expressed in Phons, which are equal to the SPL at 1000 Hz [24]. Therefore, a 40 dB SPL at 1000 Hz has the same loudness level as any point along the 40 Phon contour line [24]. A second scale, the Sone scale, was developed to represent subjective loudness and is proportional to the loudness perceived by an individual [4]. The Sone scale has been more relatable to members of the general public than the Phon scale because the conversion is much more relatable. For example, if a sound is perceived to be twice as loud as a 1 Sone sound, it is given a value of 2 Sones. Moreover, 1 Sone is defined as the loudness of a sound equal to a loudness level of 40 Phons, so 50 Phons is 2 Sones, 60 Phons is 4 Sones, etc. [4].

The basis for determining the proper method to verify loudness and its effects is described under ISO 532 Method B (Zwicker's Method); Method A (Stephens's Method) also provides a measure of loudness, but it is less commonly used [25]. Method A utilizes physical measurements obtained from spectrum analysis in terms of octave bands and is specifically recommended for its simplicity [25]. However, Method A can only accommodate measurements within a diffuse sound field and is therefore inadequate for use within *Directive 038: Noise Control*. Method B can be determined in terms of loudness (Sones: GD or GF) or loudness level (Phons: GD or GF) [26]. Selected Phon contour lines can be inverted to obtain A-, B-, and C-weighting curves. From this initial information, loudness seems to provide an efficient means for approximating LFN [26].

To fully evaluate Zwicker's Method's capability, the ERCB undertook detailed field trials comparing cases where there was suspected LFN and others where there was no significant LFN component. The thought was to then use loudness and the ratio of loudness in Sones to the A-weighted SPL to establish an adjustment factor (Table 1) that could be added to the L_{Aeq} monitoring results for the purposes of compliance testing [10]. This adjustment was applicable when loudness calculations met the criteria for LFN, had a value greater than or equal to 1.75 Sones, and had a ratio of Sone to A-weighted SPL greater than 0.05 [10]. A table was then established to select the appropriate adjustment factor that could be added to the L_{Aeq} monitoring results to

determine compliance. Initial results showed that when there were loudness levels greater than 1.75 Sones, an LFN could be identified.

Table 1: Proposed Adjustment Factors in dB (L_{Aeq}) Using Loudness [10]

Sone (S)	Ratio S/A-weighted SPL	Value (dB L_{Aeq})
1.75 – 2.00	0.050 – 0.100	+3
> 2.00	0.050 – 0.100	+4
> 2.00	> 0.100	+5

This approach was very encouraging at first and the ERCB believed that this new metric and adjustment factor would work well with the current requirements. However, the ERCB had only a small number of sound meters that could measure loudness, so adopting this technique would have resulted in an added expense. The issue became moot when additional field trials at facilities that clearly did not have any significant LFN component resulted in loudness levels that exceeded 1.75 Sones. In some cases, it was even found that loudness levels could be generally low while perceived annoyance was very high [10]. The ERCB decided to abandon any further work with loudness given its inability to discriminate LFN sources effectively.

5. ALTERNATIVE MEASUREMENT TECHNIQUES

Three different measurement techniques have been developed and put in place for current noise issues in Alberta using the C-weighted scale along with the A-weighted scale. Technique 1 is slightly more lenient with respect to current regulatory requirements and would leave the majority of gas plants and compressor stations in compliance with *Directive 038: Noise Control*. However, the few facilities that have serious problems with LFN would certainly be identified if this new metric were incorporated into future legislation. Technique 2 takes a more stringent approach. It incorporates the same method of locating the presence of LFN as Technique 1, but also requires that a 1/3 octave band spectrum analysis be performed. Technique 3 develops a simple table to find acceptable values for all of the low frequency bands based on established research.

5.1) Technique 1

The first technique calculates the difference between the L_{Ceq} and L_{Aeq} values collected from a comprehensive sound survey, and as stated earlier the magnitude of difference between the two scales of measurement can determine if a low frequency component likely exists.

The ERCB's decision to legalise the difference equal to or greater than 20 dB (between the L_{Ceq} and L_{Aeq} values) was considered abnormal in comparison with the

Internationally Standardized Weighting Curves for sound level meters [4]. C-weighted and A-weighted measurements, according to these curves, begin to deviate at a frequency around 300 Hz, increasing to a spread of 10 dB at 200 Hz and nearly 30 dB at 50 Hz [4]. Field measurements taken at residents' homes should be under representative conditions (defined by *Directive 038: Noise Control*) and be conducted for a period of at least one nighttime interval (10:00 p.m. to 7:00 a.m.). In addition, all noise surveys conducted by the ERCB require local wind condition measurements, taken throughout the monitoring period, to be assessed for direction and speed because wind generates high levels of LFN that can mask or confuse the assessment of industrial LFN [4].

Most Alberta residents should be comfortable with 20 dB between the L_{Ceq} and L_{Aeq} values. Values less than 20 dB are quite common; values greater than 20 dB correlate strongly with complaints where the expressed symptoms have been consistent with typical LFN annoyance. Where the difference between scales is less than 20 dB, most of the residents are able to accept the remnants of industrial noise that is in compliance with the current ERCB requirements.

During the field testing of Technique 1, a frequency analysis was also performed to see if there were any additional data that might be assembled. The spectrum bar graph was assessed to see if it displayed any tonal components, particularly between the 20 and 250 Hz band range. Berglund and Lindvall (1995) suggested that without the presence of a distinct tonal component, LFN may contribute to the noise environment but should not cause excessive annoyance to the average individual [5].

Directive 038: Noise Control has defined specific conditions for determining the presence of any tonal component, and it is as follows [1]:

- ◆ *The linear sound level of one band must be 10 dB or more above adjacent bands within two 1/3 octave bandwidths, and there must be a minimum of a 5 dB drop from the band showing the pronounced tone within two bandwidths on the opposite side.*

Table 2 demonstrates how the ERCB determines an LFN component. In the example given below, a tonal component is evident at 250 Hz (≥ 10 dBA within 2 bandwidths on one side and ≥ 5 dBA drop within 2 bandwidths on the other side, in addition to being pronounced within the spectrum).

Table 2: 1/3 Octave Band Frequency Spectrum Table Used for Tonal Component Analysis [1]

		Part 1		Part 2
		Maximum Δ dBA		Pronounced Within the Spectrum
Band (Hz)	Sound Level (dBA)	Within 2 Bandwidths	≥ 5 dBA on Other Side	
20	10	-4	n/a	n/a
25	12	-2	n/a	n/a

31.5	14	4	n/a	n/a
40	13	-4	n/a	n/a
50	14	-3	n/a	n/a
63	17	4	n/a	n/a
80	14	-6	n/a	n/a
100	15	-8	n/a	n/a
125	20	-8	n/a	n/a
160	23	-11	n/a	n/a
200	28	8	n/a	n/a
250	34	11	yes	yes
315	31	3	n/a	n/a
400	28	-6	n/a	n/a

Technique 1 was field tested using a large array of comprehensive survey data. The results of one case study, identified as Residence A, are as follows. The noise level during the nighttime period was 42.1 dB L_{Aeq} and 64.0 dB L_{Ceq} . The difference between the L_{Ceq} and L_{Aeq} was 21.9 dB. This result clearly exceeds the 20 dB difference between the weighting networks; consequently, according to the criteria of Technique 1, LFN may exist. The resident in this case described in detail the clear impacts of LFN including headaches, sleep disturbance, and irritability.

In fact, the spectrum analysis (Figure 1) showed a pronounced tonal component in the low frequency range at 63 Hz. The difference is 16.3 dB between the 50 Hz band and 13.3 dB between the 80 Hz 1/3 octave band. This satisfied the spectrum analysis criteria, clearly demonstrating a low frequency tonal component at 63 Hz. Therefore, a penalty of 5 dBA would have been added to the CSL, potentially making the industrial facility noncompliant with *Directive 038: Noise Control*.

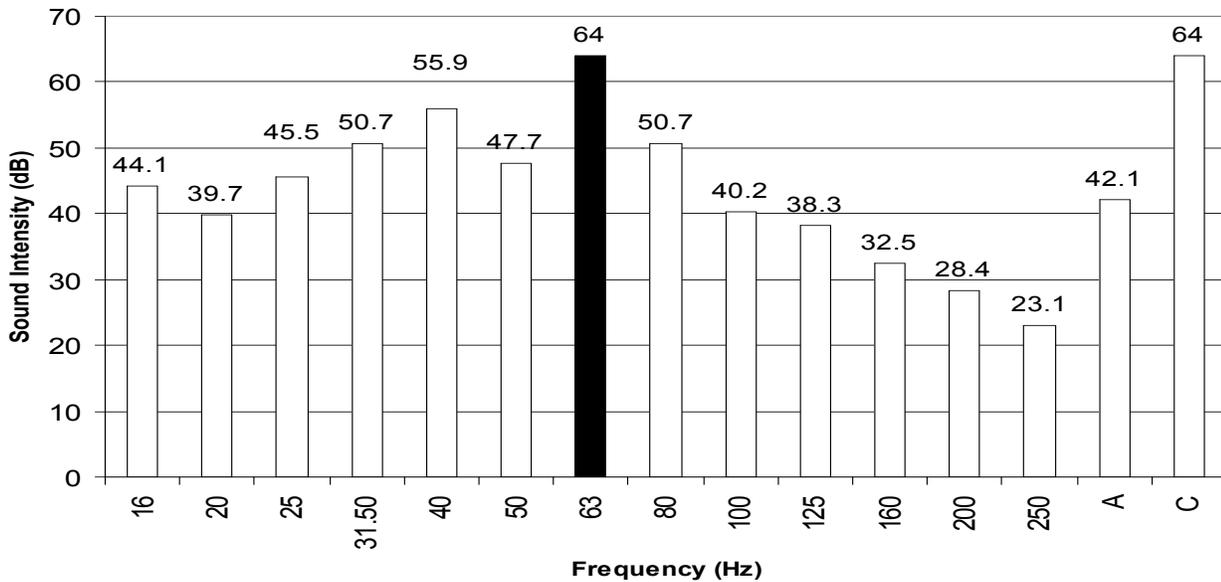


Figure 1: Low Frequency Spectrum (Facility Isolated) L_{Leq} for Residence A During the Nighttime Period of 10:00 p.m. – 7:00 a.m.

Another case study, identified as Residence B, was also analyzed using Technique 1. The sound level readings were 60.3 dB L_{Ceq} and 40.0 dB L_{Aeq} respectively. The difference between the two readings is 20.3 dB. A spectrum analysis (Figure 2) shows, however, that there is no pronounced tonal component. The resident confirmed in an interview that they did not experience any of the symptoms associated with LFN. A written evaluation between the resident and sound survey technician should be conducted to support the claim that LFN is not an issue. Standard noise control measures at the industrial facility addressed the problem by reducing the SPL at the residence to within the ERCB regulatory limits. Since the spectral analysis did not determine an LFN component, no adjustment to the CSL was made. Technique 1 should help address the way in which annoyance is related to LFN; however, the ERCB takes the view that a more stringent method should be used.

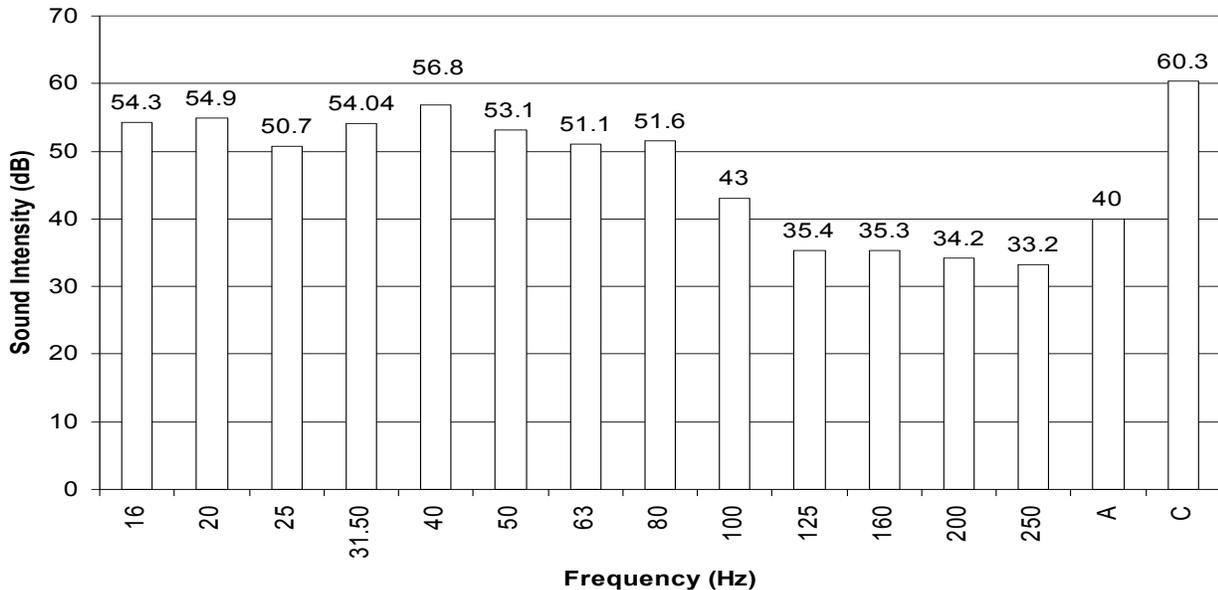


Figure 2: Low Frequency Spectrum (Facility Isolated) L_{Leq} for Residence B During the Nighttime Period of 10:00 p.m. – 7:00 a.m.

5.2) Technique 2

The second technique uses the 20 dB difference from the L_{Ceq} and L_{Aeq} readings used in Technique 1, but also includes the requirement that a tonal component must also exist in the low frequency range (20 to 250 Hz). The amplitude for the spectrum analysis should always be in linear units (dB L_{Leq}) because the level of annoyance associated with LFN is directly related to the magnitude in which frequencies differ from one another. In most situations a decreasing slope of the spectral graph will be observed.

If the difference between adjacent octave bands is more than 10 dB, or the difference between 1/3 octave bands is more than 5 dB consecutively for at least four 1/3 octave bandwidths, it is believed that an increased annoyance with LFN will likely be expressed. The mentioned value of 10 dB per octave band or 5 dB per 1/3 octave band was arrived at rather arbitrarily because it was believed that a lesser amount would be too small of a decrease for analyzing field data, and it may be too hard for existing facilities to meet that standard [10].

Pink noise could reduce annoyance levels when SPLs at each frequency decrease at a rate of less than 5 dB per octave band [27]. With industrial facility noise measured at the receptor location, usually some distance away, the low frequency component dominates the spectrum. The ERCB documented that if the transition in the spectrum from low frequencies to high frequencies was not gradual, LFN was often noticed by nearby residents in the sound environment (even though SPLs were below the 40 dB L_{Aeq} permissible limit for most rural residences).

A representative number of field tests using Technique 2 were performed, one of which is identified as Residence C. In this case, the resident complained of noise affecting their sleep patterns due to its constant presence in and around the home. This technique looked at data where the difference between the L_{Ceq} and L_{Aeq} was greater than 20 dB. Also a full spectrum analysis was performed to determine if LFN was a major factor. The SPL readings were 55.5 L_{Ceq} and 37.7 L_{Aeq} , a difference of 17.8 dB. The full spectrum 1/3 octave band analysis (Figure 3) was able to show a decrease of more than 5 dB for four successive octave bands between 63 Hz to 125 Hz. The overall difference in SPLs was 12.9 dB, which is above the 10 dB limit for Technique 2, confirming a low frequency tonal component.

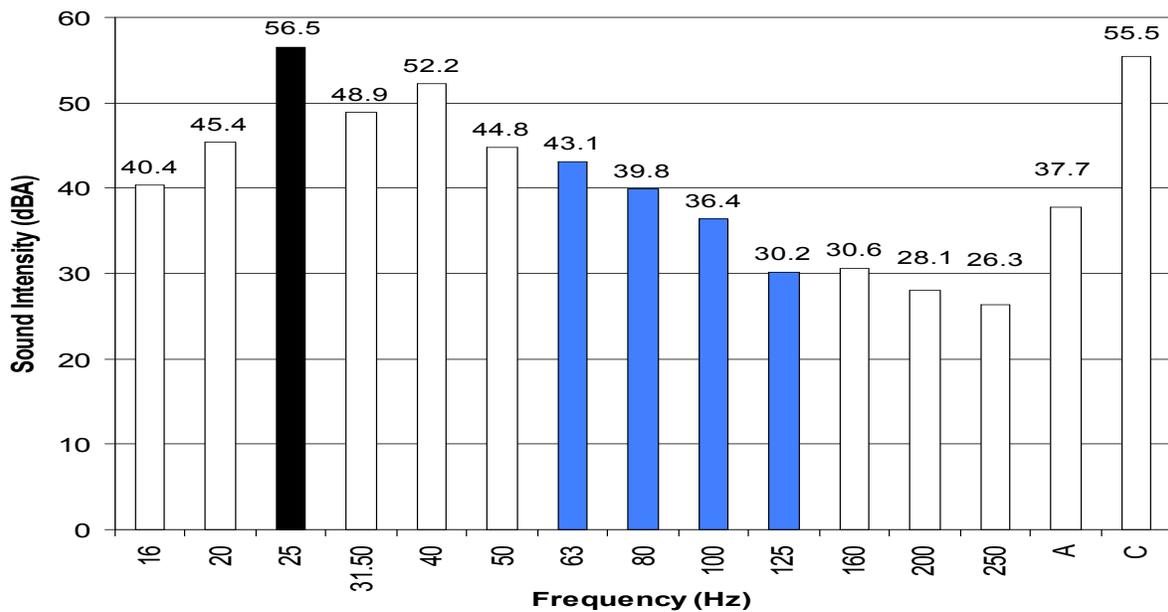


Figure 3: Low Frequency Spectrum (Facility Isolated) L_{Leq} for Residence C During the Nighttime Period of 10:00 p.m. – 7:00 a.m.

Another case study, Residence D, showed measured readings of 56.4 L_{Ceq} and 39.9 L_{Aeq} , a difference of 16.5 dB. A spectrum analysis (Figure 4) was performed using the prescribed method above, which showed that between the 40 Hz to 80 Hz bands there was a decrease less than 5 dB per band and, therefore, no tonal component was present. In this case, LFN was not identified using Technique 2. Unless the resident complained about excessive annoyance consistent with LFN descriptors, the industrial operator would only have to demonstrate compliance with the ERCB regulatory requirements as they currently exist and would not have to take extraordinary steps to address a specific tonal component.

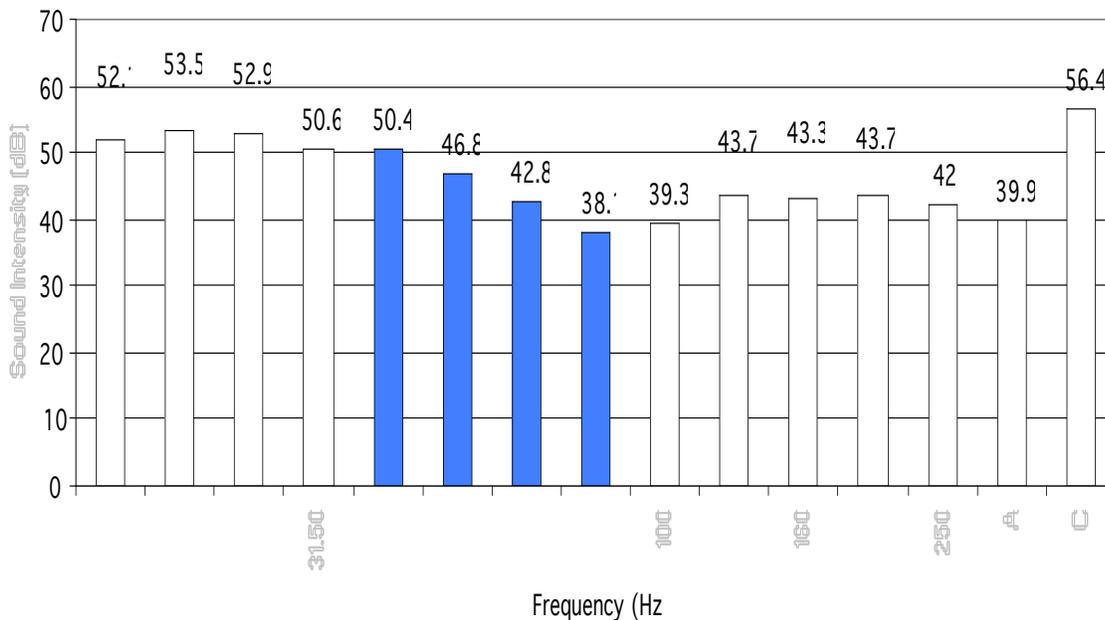


Figure 4: Low Frequency Spectrum (Facility Isolated) L_{Leq} for Residence D During the Nighttime Period of 10:00 p.m. – 7:00 a.m.

The average nighttime rural ambient sound level in Alberta is 35 dB L_{Aeq} , allowing facilities to emit noise levels up to 37 dB L_{Aeq} to meet the PSL of 40 dB L_{Aeq} [1]. The penalty adjustment of 5 dB L_{Aeq} when valid LFN concerns arise can be found to be a better alternative than simply reducing the PSL by 5 dB L_{Aeq} , which is very unrealistic. With the 5 dB L_{Aeq} penalty, only significant emitters of LFN would be affected by the adjustment.

Using the frequency spectrum as an additional tool will verify the presence of a low frequency tone that is unpleasant. Without the presence of a distinct tonal component, the LFN may have a large contribution to noise but should not be easily detected nor cause great annoyance to the average resident. A written evaluation of the sound environment concerning LFN should also be included with the noise assessment. Either the resident, the technician conducting the survey, or both should comment on the severity of the noise level and the presence of a low rumble sound or vibration and make note of it in the evaluation.

5.3) Technique 3

Another technique when performing a spectrum analysis is using a simple table to find acceptable values for all of the low frequency bands. The use of tables is very attractive in terms of ease of use but needs to be based on solid data where all examples of LFN can be identified.

The following two tables (3 and 4) are examples of an approach used in noise control regulations in the state of Oregon, USA, for analysis of LFN [28]. The first table represents permissible octave band measurements for LFN, which were not surpassed by the values presented in the examples shown in Techniques 1 and 2. The second table shows that 40, 50, 63, 100, 125, and 200 Hz octave bands were surpassed by the sound levels measured in the case studies above.

Using the data from these tables does not appear to give conclusive results similar to Technique 1 when using only C-weighting minus A-weighting values. As it can be seen, Technique 2 is quite similar to Technique 1 except that it takes a much more thorough approach. The advantage of Technique 2 is that more cases of LFN will be routinely identified, reducing the likelihood of missing a genuine concern. The disadvantage of course is the probability that some cases of LFN will result where the matter could have been solved with a less technical approach. However, more research must be conducted to verify the validity of Technique 2 using a variety of objective data to determine if it may have some role in the future.

Table 3: Allowable Octave Band SPLs for LFN in Oregon, USA [28]

Permissible Levels per Octave Band	
Octave Band Frequency (Hz)	Nighttime Sound Level 10:00 p.m. - 7:00 a.m. (dB)
31.5	65
63	62
125	56
250	50

Table 4: Allowable Sound Intensities for Each 1/3 Octave Band for Indoor Spaces in Oregon, USA [28]

Frequency (Hz)	Sound Intensity (dB)
31.5	56
40	49
50	43
63	41.5
80	40
100	38
125	36
160	34
200	32

5.4) Possible Improvements to the Above Techniques

An improvement that could be made to Technique 1 consists of determining the important 1/3 octave bands and the tones associated with them that would cause a significant amount of annoyance. Due to the threshold of human hearing, 1/3 octave bands that are below 31.5 Hz must have a sound intensity above 60 dB in order to be heard [22]. This could lead to only being able to use tonal components above 31.5 Hz and below 200 Hz to satisfy the criteria from Technique 1. However, if a large tonal component exists below 31.5 Hz, vibrations may occur that could cause annoyance to the resident. Therefore, it may be justified to perform a complete spectrum analysis in the entire low frequency range.

An improvement that could be made to Technique 2 is to determine what octave bands would cause the most annoyance to the resident, similar to what was discussed in the preceding paragraph. Another improvement could be to determine whether the 5 dB per 1/3 octave band decrease is too small a margin when analyzing free field data. Leventhall (2005) indicated that about 10% of the population may have a threshold that is 10 dB or greater compared to the median (50%) threshold, demonstrating that LFN may be problematic for a small number of people [29]. Moreover, van den Berg (1999) stated that if the hearing threshold for 50% of the population (Table 2) has been exceeded in the low frequency range, then LFN must be reduced [30].

6. LFN REGULATIONS IN OTHER JURISDICTIONS

Now that the impacts of LFN were better understood and potential metrics identified, the last objective involved looking at what other countries were doing around the world and perhaps learning from their experiences.

Sweden has designed maximum LFN levels for each octave band and has incorporated them into their 1999 indoor building regulations with established L_{Aeq} values for every frequency [31]. The table below shows some common frequencies and their associated L_{Aeq} values. The advantages of this method is that it would not require expensive equipment and computer program changes, and A-weighting would still be retained within *Directive 038: Noise Control*, causing minor changes to the directive. At this moment, one major disadvantage to such a system is that regulations like these may be difficult to comply with. In addition, as the number of regulating sound level values increase in *Directive 038: Noise Control*, the more insignificant each number becomes.

Table 5: Swedish LFN Regulations for Indoor Buildings [31]

Frequency (Hz)	L_{Aeq} (dBA)
160	32
200	32
31.5	36
40	49
50	43
63	41.5
80	40
100	38
125	36

Establishing regulations similar to those in Sweden is a proven way to account for LFN in a sound survey. Furthermore, the extent to which C-weighting and loudness accounts for LFN is a disputed issue, while regulations such as Sweden’s have been successful in addressing LFN problems. A system similar to Sweden’s requirements has the potential to be incorporated into future editions of *Directive 038: Noise Control*, but further research and field testing would have to be conducted to obtain values that represent annoyance levels for communities affected by industrial energy facilities that would be applicable to Alberta residents.

Another European standard, used by the Dutch Noise Annoyance Foundation (2002), appears to have had some success in identifying LFN problem areas [32]. Under the Dutch standard, measured sound levels are compared to the 90% hearing threshold levels for (ontologically nonselected) people aged 50 to 60 years as determined by Passchier-Vermeer (1998) [32]. Although there has been some success with regard to LFN regulation, more works need to be done to fully resolve the issue in that country.

One of the most promising guidelines to come out of Europe is the German national standard DIN 45680, 2002 [11]. Its values (designed by Piorr and Wietlake) are based on an A-weighting of 1/3 octave band levels in the range of 10 to 100 Hz. Table 6 shows the nighttime and daytime limits that correspond to the 50% auditory threshold. It must be noted that these values can only be applied for LFN with “unusual” character (e.g., having an intense fluctuating nature); the measurement area needs to have low background noise levels so that the LFN dominates and the LFN must have a substantial tonal component [11].

Table 6: German National Standard DIN 45680 for Nighttime and Daytime LFN Thresholds [11]

Nighttime											
Frequency (Hz)	10	12.5	16	20	25	31.5	40	50	63	80	100
L _{Aeq} (dBA)	95	86.5	79	71	63	55.5	48	40	33.5	33	33.5
Daytime											
Frequency (Hz)	10	12.5	16	20	25	31.5	40	50	63	80	100
L _{Aeq} (dBA)	100	91.5	74	75	68	100.5	53	45	38.5	38	38.5

7. DISCUSSION OF RESULTS

Currently, there does not appear to be a single metric that can be used for LFN and non-LFN situations. Technique 1 could be the simplest way to identify LFN problems and would not cause major adjustments to current acoustical equipment inventories or

measurement methodologies here in Alberta, but it is susceptible to erroneous results. An improvement to Technique 1 would be to perform a complete spectrum analysis, which could identify a tonal component in the low frequency range that would likely be the source of annoyance.

Technique 2 proved that a difference approaching or greater than 20 dB between the L_{Ceq} and L_{Aeq} measurements, along with an appropriate spectrum analysis confirming a tonal component, can yield valid results regarding the presence of LFN. Impacts on nearby residents due to industrial noise should be minimal if the ERCB requirements are met.

Leventhall (2006) suggested that the best way to solve the problem with LFN is to lower the maximum sound levels allowed to somewhere below the hearing threshold for the majority of the population [29]. Since an individual's hearing threshold can be up to 10 dB below the current (average) ambient levels regulators like the ERCB use today [29], Leventhall advocated a PSL 5 to 10 dB lower than the current limits. This could be quite problematic because most facilities in Alberta today are just under the 40 dB L_{Aeq} nighttime PSL at the nearest or most impacted residence. Any new ERCB regulations lowering the PSL would put a majority of facilities in jeopardy or create the necessity for a grandfathering clause, which could potentially result in a different PSL for the same residence depending on whether a facility is new or grandfathered. This would undoubtedly result in an administrative nightmare from the point of view of a provincial regulator.

8. CONCLUSION

As industry and the rural population of Alberta grow continue to grow, the effects of noise may become more problematic. Both field testing and research were used to understand the impacts of LFN and to determine how to properly address it, specifically with regard to *Directive 038: Noise Control*. The research undertaken by the ERCB focused primarily on physical and mental health issues related to LFN. The conclusions were clear: the metric L_{Aeq} fails to properly account for the presence of LFN in CSL survey data, and LFN can have serious negative effects on an individual's quality of life. For this reason, it remains the duty of the ERCB to implement regulations that will account for LFN to the extent possible. As a result of this work, the 2007 edition of *Directive 038: Noise Control* made the following mandatory [33]:

- ◆ An NIA must be completed prior to application submission for new permanent facilities and modifications to existing permanent facilities. The NIA will help to identify the expected sound level and any possible LFN contribution from a facility on the most impacted residence. In addition, this assessment before initiation of the project would determine whether the facility would meet *Directive 038: Noise Control* standards, helping to reduce retrofitting of facilities as a method of noise mitigation.

- ◆ Sound monitoring and surveying device(s) must be capable of continuously measuring both L_{Aeq} and L_{Ceq} readings simultaneously. A dual-channel capable sound level meter that can obtain both the A- and C-weighting sound levels simultaneously may also be used.
- ◆ In order to be classified as an LFN problem, the isolated (i.e., nonfacility noise, wind noise, etc., removed) L_{Ceq} minus L_{Aeq} value for the measured nighttime period must be equal to or greater than 20 dB, and a clear tonal component must exist at a frequency below 250 Hz, using appropriate spectrum analysis.
- ◆ Any facility found to have a qualified LFN component will have an adjustment of +5 dBA added to the CSL monitoring result that will then be compared to the PSL to determine if the facility is in compliance with the requirements. For example, if the representative noise survey resulted in a CSL at a residence of 38.7 L_{Aeq} and the PSL was 40 L_{Aeq} , but an LFN situation was confirmed using the appropriate criteria, a 5 dB adjustment would be added to the CSL, giving a value of 43.7 L_{Aeq} . This would then necessitate a minimum 3.7 dB L_{Aeq} noise reduction, including addressing the source of the tonal component, to put the industrial facility in compliance.

The ERCB has determined that LFN is an issue that must be resolved quickly and accurately to improve the sound environment and quality of life for the residents of Alberta, Canada. The ERCB believes that this approach to environmental noise control legislation will not be overly punitive to industry in achieving compliance nor complex for users to administer. The ERCB is fully confident that the outcome will be a reduction of LFN issues, with an added benefit of improved relationships between rural residents and industrial operators.

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