Proposed criteria in residential communities for low-frequency noise emissions from industrial sources

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Excessive low-frequency noise from open-cycle combustion turbine power plants has been recognized as a serious noise and vibration problem since the early 1970s. Yet, the problem still occurs, mainly because siting and specifying agencies are largely uninformed about the problem and because there are no standardized noise criteria in the U.S. to consult for guidance in avoiding low-frequency noise problems. Detailed sound pressure level measurements from five low-frequency problem sites are analyzed for support of a proposed criterion. The data are compared to noise and vibration thresholds. In addition, a small sampling of responses from residents to varied levels of low-frequency noise immissions is presented. This paper proposes a "C" weighted overall sound level criterion. The proposed criterion should be applicable to most industrial sources of steady low-frequency noise in addition to combustion turbines.

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1. INTRODUCTION

This paper proposes C-weighted overall level limits necessary to avoid, or at least minimize, resident complaints from low-frequency industrial sources. The proposed limits are developed mainly from experience at problem installations using open-cycle combustion turbines for peak power generation. Figure 1 shows two types of turbine models.

In an open-cycle operation, combustion turbine exhaust gases are discharged directly into the atmosphere through a silencer/stack system, as pictured. Low-frequency noise problems are typically associated with exhaust stack emissions from *open-cycle* turbine plants as opposed to *closed-cycle* service. In a closed cycle, exhaust gases are directed into a massive heat recovery steam generator (HRSG). Power companies use open-cycle plants to drive generators for peak

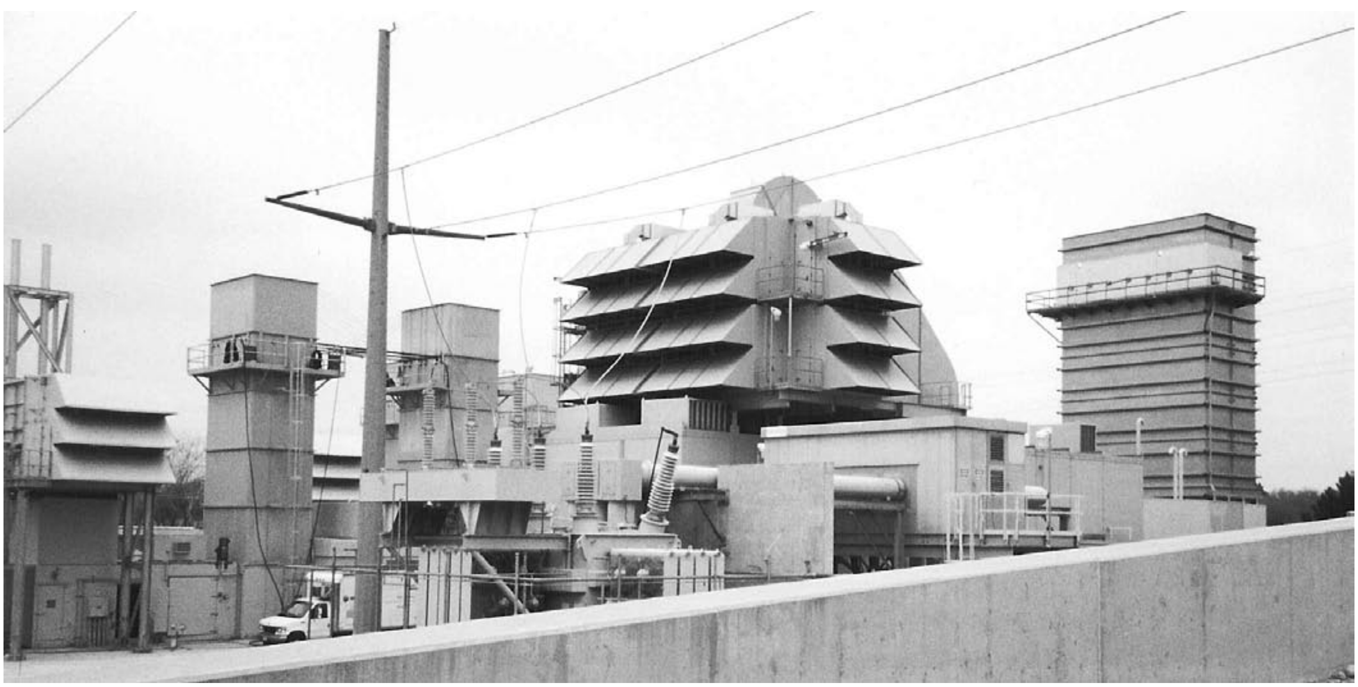

Fig. 1– An aero-derivative combustion turbine (unit with dual stacks) rated at 50 MW next to an industrial combustion turbine rated at 120 MW. Hooded assemblies are combustion air inlets. Vertical rectangular stack assemblies are turbine exhaust silencers venting to atmosphere.

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load applications and to drive compressors for gas and liquid pipelines.

Peak electrical loads usually occur during very hot summer months and/or very cold winter months. Typically the units may operate daily during these periods, starting in early afternoon and shutting down by midnight. Units operate 24/7 for pipeline applications.

As early as 1971, ANSI B133.8, "Gas Turbine Installation Sound Emissions," was drafted and included Appendix B that recommends a limit of 75 to 80 dB(C) to minimize the problem of low-frequency noise or infrasound problems that were surfacing at that time. Experience since then has shown that this recommendation is woefully inadequate, and that the problem continues to occur for combustion turbine open-cycle plants.

It will be shown that turbine exhaust stack emissions are tonal in nature as are most sources of low-frequency noise. For purposes of this paper, tonal is defined as a sound spectra containing one or more peak values of pressure level as measured with an FFT analyzer in narrow frequency band regions. It is believed that the proposed limits would also be valid for other steady and tonal sources of low-frequency noise, such as compressor stations, wind turbines, diesel generators, and others. The criteria are not intended for impulsive sources of infrasound.

It will also be shown that the standardized C-weighted overall level is an excellent metric for regulation purposes.

2. PURPOSE OF PROPOSED CRITERIA

The proposed criteria apply to C-weighted noise levels measured outdoors but close to residential structures. The intent is to propose levels that should prevent both a detectible fingertip feel of vibrations on the structure windows and walls, as well as the adverse sensation of sensing a low-frequency disturbance.

The main complaint from low-frequency sources is perceptible vibration, mostly inaudible unless the intensity is high enough to cause a rattling noise. These complaints are often described as a feeling in the body as opposed to the more normal audible noise problem. One could easily surmise from these descriptions that this type of problem is independent of both ambient noise quality in the area and the duration of the noise.

However, experience over the years indicates that residents located in very quiet rural environments are much more distressed by a new intrusive source of noise because of the loss of a formerly peaceful and tranquil sound environment. Conversely, there is also some greater tolerance of excessive low-frequency noise from open-cycle peaking plants that essentially operate only during very hot or very cold periods, shut down at nighttime, and do not operate for extended periods of the year.

The proposed C- weighted levels should supplement the normal A-weighted site criteria. If the C-A weighted level exceeds 20 dB, the spectrum is said to be unbalanced or the low-frequency content is excessive. Therefore, if one is considering a very quiet site requiring A-weighted levels below 40 dB, one should also consider reducing the C-weighted levels in Table 1 to not exceed 20 dB above the A-weighted level.

Lastly, the proposed criteria are derived from investigating a valid but relatively small sampling of problem sites by a single investigator. The user may want to conservatively reduce the levels by a small number to account for the variable nature of human response to low-frequency sounds.

3. PROPOSED CRITERIA

The limits tabulated in Table 1 are proposed for two classifications of ambient quality and two durations of equipment operation.

TABLE 1 – Maximum allowable C-weighted sound level, dB(C), at residential areas to minimize infrasound noise and vibration problems.

	For Normal Suburban/ Urban Residential Areas, Daytime Residual Level, L_{90}>40 dB(A)	For Very Quiet Suburban or Rural Residential Areas, Daytime Residual Level, L_{90}<40 dB(A)
For Intermittent Daytime Only or Seasonal Source Operation	70	65
Extensive or 24/7 Source Operation	65	60

4. EXPERIENCE AT PROBLEM SITES

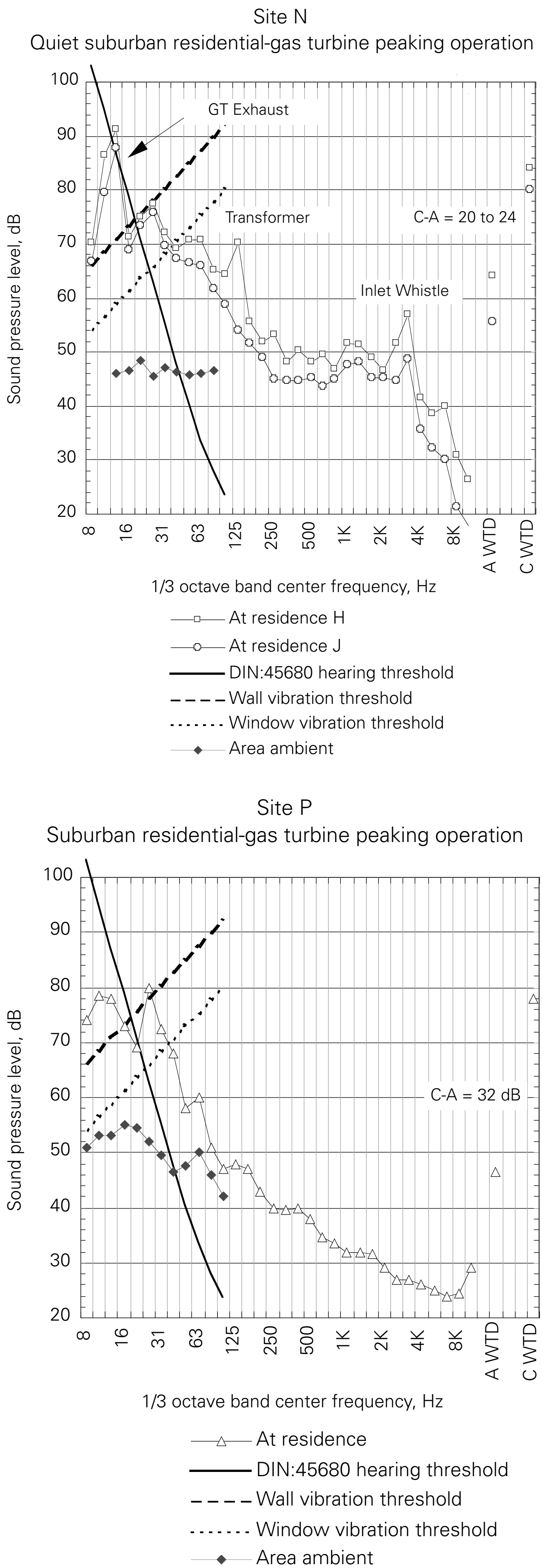
Results of investigations at five sites experiencing low-frequency noise complaints are offered to support the levels proposed in Table 1. Figures 2a through 2d plot the measured outdoor, one-third octave band spectra close to the nearest complaining residence at four turbine problem sites located throughout the United States. For evaluation and comparison purposes, the spectra for the thresholds of perception for audible low-frequency noise and tactile fingertip feel for vibration are included on all of the graphs.

The noise threshold is from the German standard DIN: 45680, 1997, which extrapolates the threshold of hearing from the ISO standard[1] from 20 Hz down to 8 Hz. The vibration threshold curves are from reference 2. The plots also include the measured C-A weighted overall level difference.

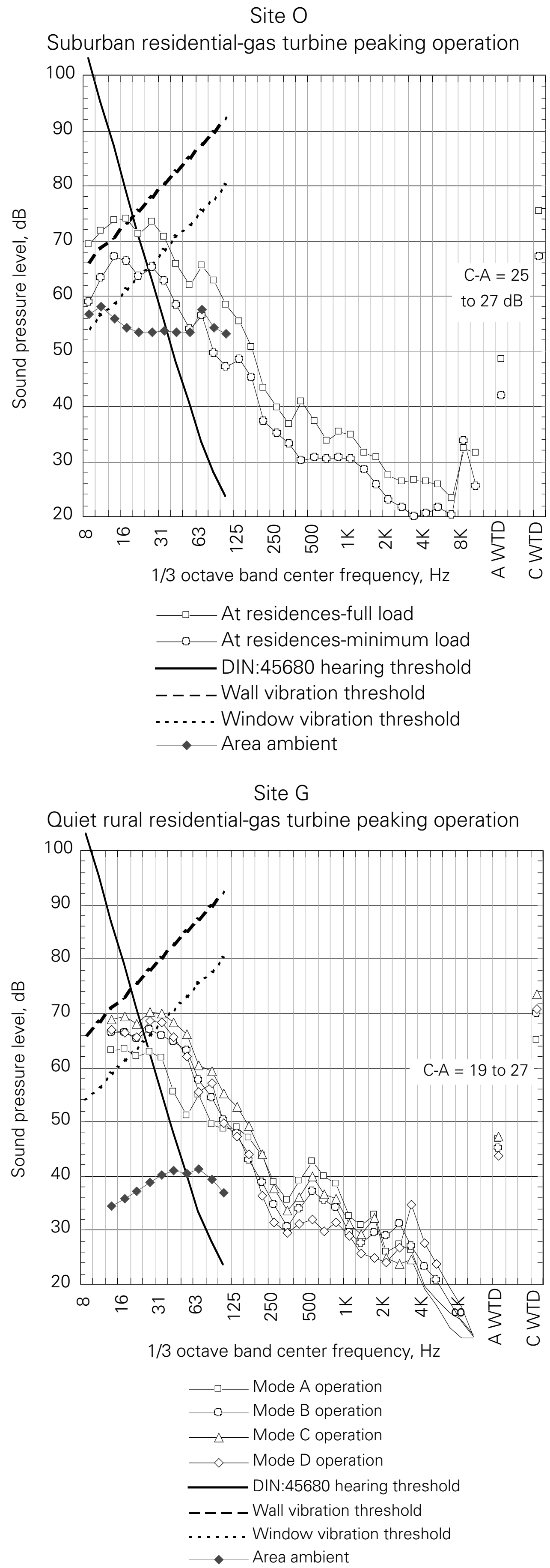
The first observation at all sites from Fig. 2 is that the commonly used indicator of C–A => 20 dB is indeed a useful barometer for detecting a spectrum with potentially excessive low-frequency noise since the difference is greater than 20 dB in all cases except one. In the one case where the C-A level difference was 19 dB (site G), the residents volunteered that the level was just acceptable although very noticeable.

Another common factor is that the threshold for perceiving window vibration is exceeded at all of the sites; at three of the four sites, the threshold for perceiving wall vibration is also exceeded. Lastly, the offending airborne noise is essentially inaudible below about 20 Hz at all sites.

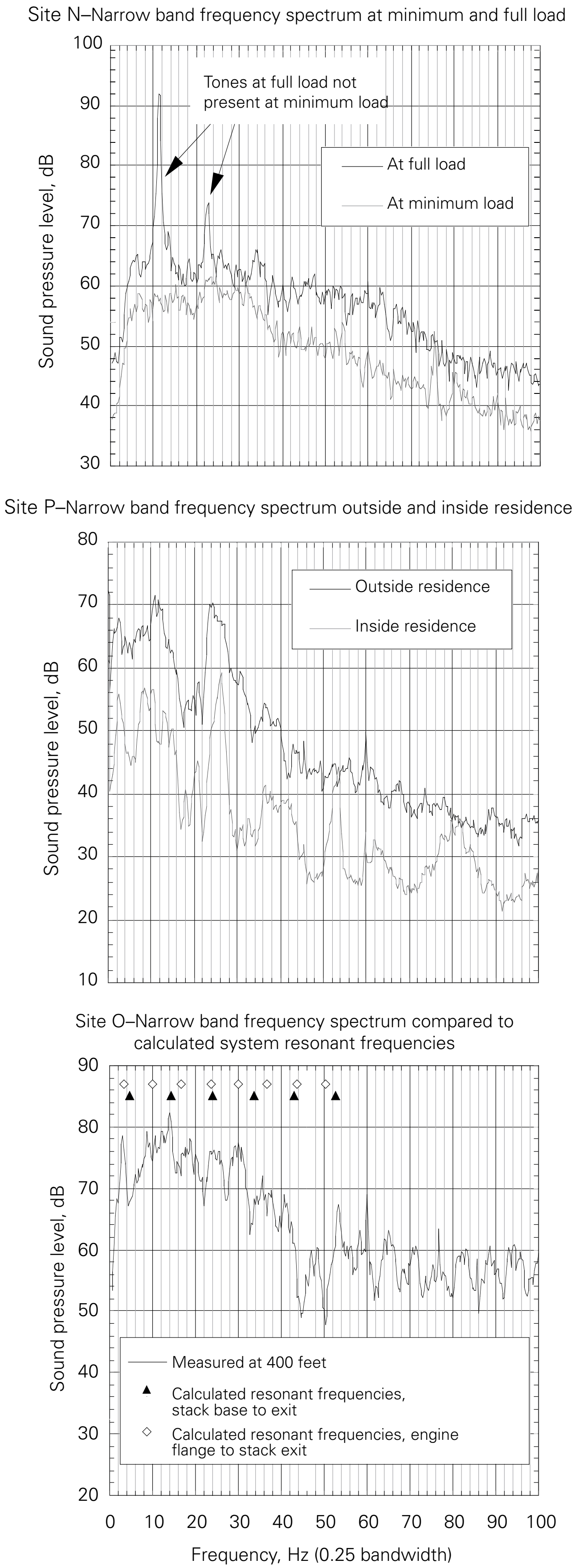
Each site is unique and additional narrow band data are



Figs. 2a and 2b– One-third octave band spectra for sites N and P.



Figs. 2c and 2d– One-third octave band spectra for sites O and G.



Figs. 3a, 3b and 3c – Narrow band spectra for sites N, P and O.

presented in Figs. 3a, 3b, and 3c to supplement the one-third octave band spectra. All indoor measurements are made in the room center and outdoor measurements are at least 15 m from any building surface. All measurements are made at a height of 1.5 m. Specific information learned at each site is described in the following section.

A. At site N

This site is rural but near a major roadway, and the two closest residences are less than 120 m from the 20 MW aero-derivative combustion turbine. The unit only operates about 200 hours per year. At partial and full load, moving reflections in mirrors, rattling doors, and a sensation or feeling of "something" was obvious inside the residence. A low-frequency noise component was less obvious but easily detectable outside of the residence.

Narrow band measurements given in Fig. 3 for this site indicate an intense tone at 11 Hz and a harmonic tone at 22 Hz, which is created at some load point beyond minimum load. All of the adverse low-frequency effects disappeared immediately when the load was reduced to minimum for the turbine, even though the audible flow generated noise is not substantially lower. This demonstrated that such very low-frequency discrete tones can and do excite the structure and cause severe disturbance.

Inspection of the engine showed erosion in the hot section combustor area. When a spare engine was installed, the offending tones were no longer created at any load, which proved that the tone was attributable to wear in the combustor cans that, in turn, created a combustor pulsation. Observations at many sites show that combustor-related pulsations typically are very narrow band, well defined tones that do not change frequency with load as the exhaust gas temperature varies. In contrast, resonant tones or peaks associated with an aerodynamic source of excitation are broader and do shift frequency with changing wavelength caused by a change in temperature of the exhaust gases at different turbine loads.

B. At sites P and O

The combustion turbines at these two sites are located on the order of 400 to 900 m from suburban residential areas with ambient noise character including local traffic and other low-level industrial sources. Both sites have 1998 or newer models of modern, high-capacity industrial combustion turbines from two different manufacturers in the range of 120 to 160 MW capacity. Such turbines have extremely complex combustors designed to minimize air emissions. Some combustor designs allow water injection both to reduce air emissions and create additional load capability by increasing the mass of the combustion gases.

The narrow band spectra for sites P and O in Fig. 3 show the more normal case of excessive low-frequency noise from large turbine exhaust systems. Note that the tones or peaks are more broadband compared to the narrow combustor tone at site N. All spectra were measured with a portable RION SA77 signal analyzer with a bandwidth of 0.25 Hz.

Kudernatsch[3] was the first to document with measurements that this tonal behavior is a function of the downstream exhaust geometry rather than the combustion turbine source. He showed that frequency peaks change and correlate with turbine exhaust gas temperature (variable speed of sound) and also with variable stack height geometry.

The resonant longitudinal modes of the silencer/stack systems can be calculated and matched to the spectra, which was done on the graph of site O. The calculation assumes a long tube with plane wave propagation, closed at one end and open at the other. Tones can be created in these systems with tall stacks (30 m in this case) as low as 3 Hz or even lower for taller stacks.

These examples show that most turbine site spectra are tonal in nature as opposed to a purely broadband aerodynamic flow noise.

At site O, the turbines are operated at minimum load for extended periods of time. This is not a common operational mode since fuel efficiency is poor at minimum load. Here, however, it is offset by a spinning reserve credit. The C-weighted level in the community was measured at 67 dB at minimum load and increased to 75 dB at full load, as shown in Fig. 2, site O.

There were few, if any, complaints at minimum load, even though turbine operation is easily detectable by listening. At full load (75 dB), the turbine low-frequency noise is easily noticeable and complaints ensue. From this experience, it was deduced that a C-weighted level of 70 dB for this type of environment is the maximum recommended level for avoiding low-frequency noise problems at sites with sporadic or seasonal operation. For extended operation in such environments, a C-weighted level of 65 dB is proposed.

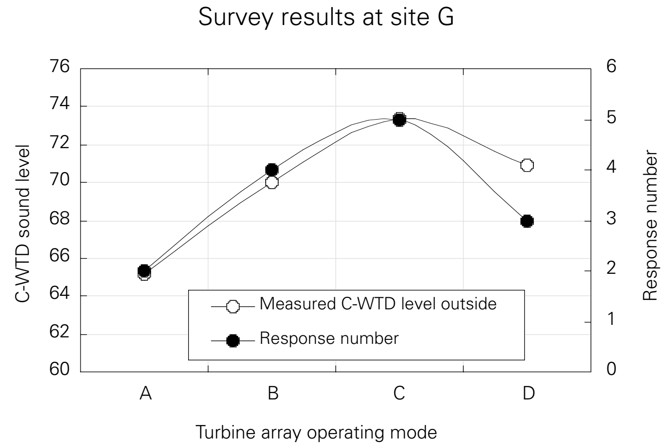
C. At site G

Site G is located in a very rural, quiet area with no nearby environmental noise sources. Complaints ensued immediately from a large widespread area during turbine operation. The site has two different turbine models and optional water injection for power augmentation. Therefore, it was possible to operate the two different turbine types to produce four operating modes that varied both the spectra and level arriving at the residence as shown in Fig. 2, site G.

The measured outdoor C-weighted level varied from 65 to 73 dB at the closest home, approximately 800 m away. The two residents at this home completed a response survey form that had five subjective degrees of response ranging from acceptable to not acceptable for each of the four immission levels.

The results are shown in the graphic titled "Survey Results at Site G." The five response degrees are numbered and plotted on the graphic. The plotted subjective response mirrors the measured C-weighted level. The technicians, consultants, and plant owner subjectively concurred with the resident's responses.

It was concluded from this very minimal survey that a C-weighted level of 65 dB is the maximum level that should be allowed for peaking turbine sites in quiet rural communities. Notice that at 65 dB, the source will be noticeable but judged to be just acceptable. For extended operation in such environments, a C-weighted level of 60 dB is proposed.



Ref, response number:
1–OK with level, acceptable
2–Noticeable, but still acceptable
3–Very noticeable, marginally acceptable
4–Annoying, not acceptable
5–Very annoying, definitely not acceptable

D. At site A

Measurements at site A shown in Figs. 4a and 4b are such that one would not suspect a severe problem with low-frequency noise. The one-third octave band spectra at the nearest complaining residence approximately 800 m (1/2 mile) from a multiple reciprocating compressor station is plotted in the top portion of the figure. A C-weighted level of 60 dB and a C-A quantity of just 13 dB would not seem problematic. Yet, the resident moved to escape the noise. Before moving, the resident would crouch behind a masonry fireplace in one corner with ear protection (cupped ears) in place to escape the noise.

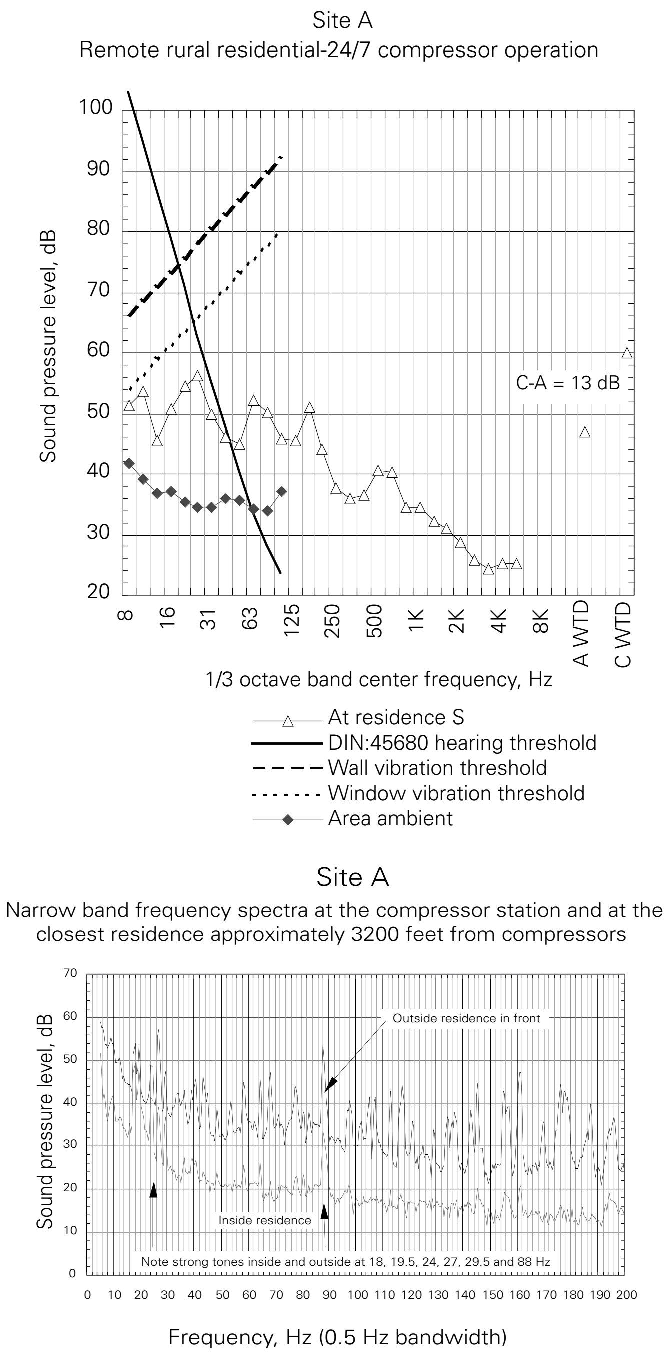
Narrow band measurements at the bottom of Fig. 4 show that the compressor tones inside the home in the 16 to 20 Hz frequency regions were nearly as high as the outdoor measurements. Since there is little sound transmission loss at very low frequencies, the spectrum inside can become unbalanced as higher frequency noise is attenuated by the house structure.

It should be noted that measurements at this site were limited to one sunny afternoon when sound propagation conditions over the long path were not favorable. It is likely that compressor noise is significantly higher at other times when atmospheric conditions are different.

It was concluded that this site study represents the worst-case scenario. The tonal compressors operate on a 24/7 schedule and the area is very rural and remote from daily sources of environmental noise. Daytime A-weighted residual levels were in the 25 to 30 dB range.

In addition, only one resident, obviously possessing a very acute sense of response, experienced such severe suffering.

Nevertheless, a new source of noise with a C-weighted level of 60 dB can sound quite loud and threatening to residents accustomed to very quiet surroundings.



Figs. 4a and 4b – One-third octave band and narrow band spectra for site A.

5. USE OF C- WEIGHTED METRIC COMPARED TO FREQUENCY CRITERIA

Most low-frequency noise criteria are expressed in terms of one-third octave band spectra near the ISO 226 definition of the threshold of audible noise. Leventhall[4] provides an excellent summary on the low-frequency noise problem that contains the control limits in use throughout the world. It is evident that a greater awareness of the problem and remedial action on low-frequency noise is happening in Europe and in Japan.

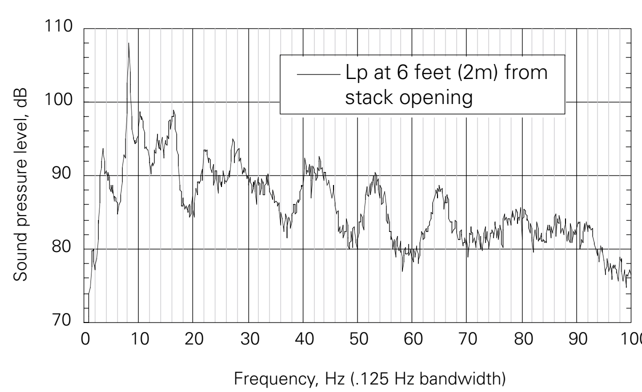
While detailed spectra shape is the preferred technical metric for understanding low-frequency noise, there are great advantages to using the simple C-weighted overall level for criterion and regulation purposes. Many of the same advantages have led to the nearly universal use of the A-weighted level for noise ordinances.

Some difficulties of using one-third octave band spectra for regulation purposes that are avoided by using the C-weighed level are:

- One-third octave analysis requires instrumentation and expertise well beyond the resources of officials responsible for enforcement.
- Low-frequency tones may fall right on a band frequency range limit. This occurred at site N at 11 Hz, which is the upper and lower limit of the 10 and 12.5 Hz one-third octave bands. This complicates the usual approach of limiting an increase in any one band above the values in adjacent bands.
- There may be multiple tones falling into a one-third octave as illustrated by the spectra of site A.

The standardized frequency weightings for sound level meter (SLM) networks are cut-off at 10 Hz. We have shown that there may be troublesome tones lower than 10 Hz and possibly, this could be a problem using the C-weighted network of a SLM with an undefined response below 10 Hz.

The measured spectrum below shows a maximum peak level tone at 8 Hz from the exhaust stack opening at site G. The 8 Hz tone is created by water injection into the combustor. The more broadband system tailpipe resonant modes discussed above are also evident. It can be shown for this spectrum that the C-weighted level calculated by simply extrapolating the weighting network down to 8 Hz is only 0.2 dB higher than the current standard cut off at 10 Hz, even though the peak level occurs below 10 Hz. This occurs because C-weighting becomes increasingly greater at lower frequencies. So, for practical purposes, the current weighting standard is not a problem. However, it should not be a difficult task to extend the standard weighting curve down to 1 Hz.



6. CONCLUSIONS

There is a need in the United States for some federal or prominent standards organization to publish limits in residential areas for low-frequency noise from industrial sources. This paper proposes maximum limits based on experience in investigating and solving low-frequency noise problems, principally from open-cycle combustion turbine installations. The author believes these problems have occurred over the past 30 years in large measure because there has been no national standard defining permissible low-frequency airborne noise in the United States.

The author and others have designed exhaust systems that greatly reduce the emission of low-frequency noise for new installations. Retrofits have also been engineered to correct problem sites, although at much greater expense compared to new sites. Nevertheless, it can be unequivocally stated that present technology is available to avoid or solve such low-frequency problems.

It is frustrating to continually witness great community distress and ill will towards a plant owner that could have been avoided. Hopefully, greater awareness of the problem and standardized limits for low-frequency noise immissions will minimize such problems.

7. REFERENCES

[1] *Acoustics-Normal Equal Loudness Level Contours*, International Standard ISO 226: 2003 (International Organization for Standardization, Geneva, Switzerland, 2003).

[2] Stephens, Shepard, Hubbard & Grosveld, "Guide to the evaluation of human exposure to noise from large wind turbines," NASA Technical Memorandum 83288, March 1982.

[3] G. Kudernatsch, "Combustion Turbine Exhaust Systems-Low Frequency Noise Reduction," Proc. INTER-NOISE 2000, edited by Didier Cassereau (Noise Control Foundation, Poughkeepsie, New York, 2000).

[4] G. Leventhall, "A Review of Published Research on Low Frequency Noise and its Effects," Report for Department for Environment, Food and Rural Affairs, London, UK, May 2003