THE IMPORTANCE OF LOW FREQUENCIES IN NOISE ANNOYANCE

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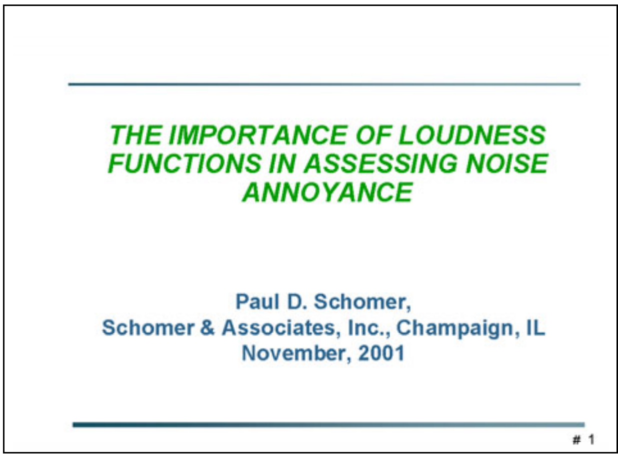
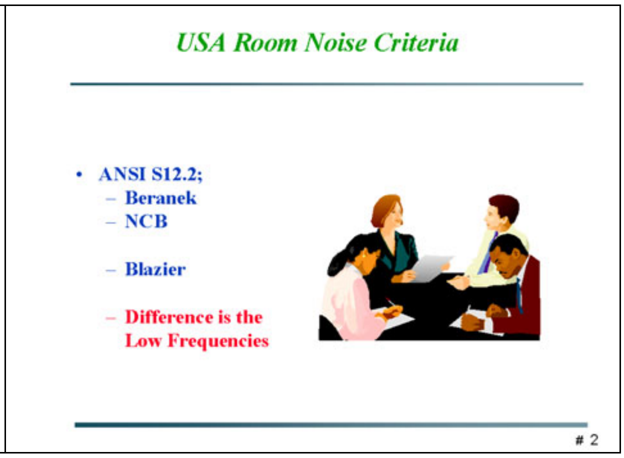
1. INTRODUCTION

(SLIDE 1) Good day ladies and gentlemen and honored chairperson. I wish to thank you for inviting me to give this lecture and apologize that I am unable to give this talk in Portuguese. As you know, we in the United States are very poor at all languages including English. Just ask anyone from the England. While we may not speak the same language, we share many common problems. And one thing that we know is that noise bothers and annoys people. But how do we assess the noise? Assessing noise, either outdoors or indoors, remains a subject of great controversy and debate.

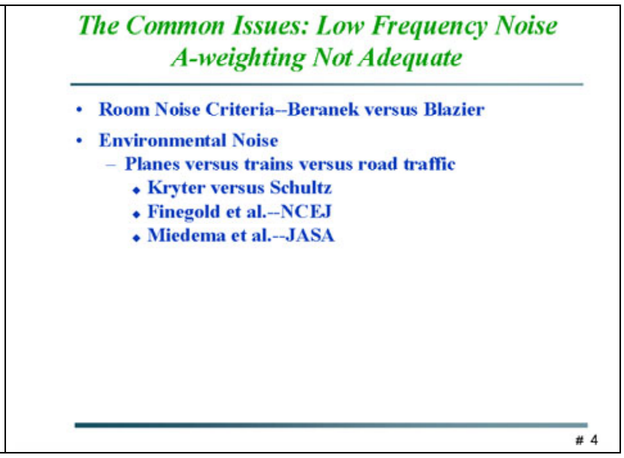




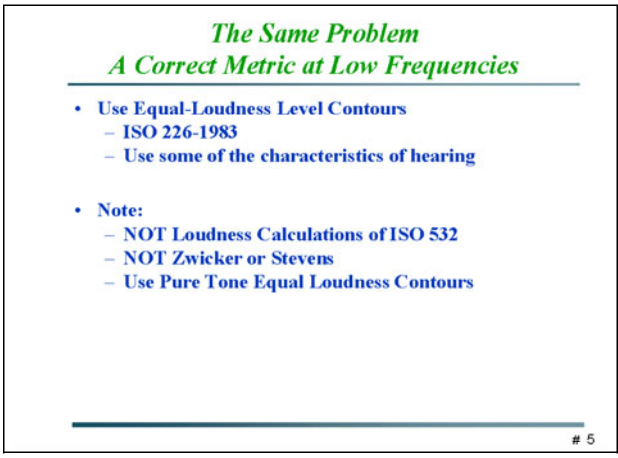
(SLIDE 2) In the United States, there has been an ongoing controversy dealing with architectural room noise criteria. Beranek has proposed modifications to his Noise Criteria (NC) curves and termed these NCB. Blazier has proposed RC curves. These two sets of curves differ markedly at low frequencies. As a result, our current American National Standard on this topic, ANSI S12.2—Room Noise Criteria, contains two separate appendices—one with the RC procedure and one with the NCB procedure.

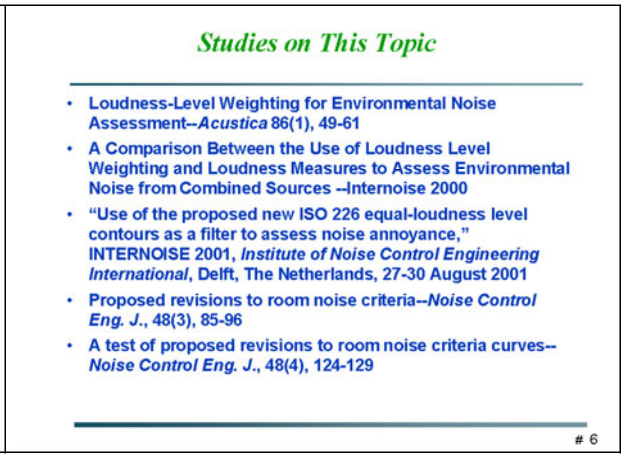
(SLIDE 3) Outdoors, there is great worldwide interest in creating the ability to assess all common community noise sources in a combined fashion with one common noise metric and corresponding criteria. That is, there is the desire to assess road traffic, railroad, aircraft, industrial, and neighborhood noises all together with one common metric. In the United States, we have a relatively new set of American National Standards on this topic, ANSI S12.9 Part 4 which deals with Assessment of Noise; Part 5 which deals with compatible land use; and Part 6 which deals with sleep disruption. In Europe, there is a plan to map the noise in every city where the population exceeds 250 000. Initially, they will include road traffic, railroad and aircraft noise. Eventually they will include other noises and extend down to cities where the population exceeds 50 000. At the International Organization for Standardization (ISO), we are trying to revise ISO 1996 and deal with this issue.

(SLIDE 4) For years, many have suggested that A-weighting was inadequate for assessing combined noise environments. In the famous Kryter-Schultz debate in JASA (1978, 1982), Kryter took issue with Schultz and suggested that for the same A-weighted day-night sound level (DNL), aircraft noise was more annoying than road traffic noise. Recently, in a paper in Noise Control Engineering Journal (1994), Finegold and von Gierke *et al.* from the United States suggest that there are indeed systematic differences in annoyance between aircraft, road traffic, and railroad noise for the same DNL, and they offer a set of curves to show these differences. In an even more recent paper in JASA, Miedema (1998) offers yet another set of curves that show differences between the annoyance generated by aircraft, road traffic, and railroad noise for the same DNL.



(SLIDE 5) In today's talk, I suggest that the Beranek-Blazier controversy and the controversy over assessing combined environmental noise situations are really both part of the same issue. Noise assessment, either indoors or outdoors, requires that we properly note and assess the low frequency content of the sound. Today, I will show that the methods of both Beranek and Blazier fail to properly account for low frequency sound. When one does properly account for the low frequency sound, then the two methods merge together. For environment noise, I will show that much of the reported differences between transportation noise sources are due to not properly assessing the contribution of the low frequency sound. In both cases, I will make use of the equal-loudness level contours found in ISO 226-1987. Please note, I am not talking about loudness calculations as are given by researchers such as Zwicker or Stevens. My method does not use the loudness calculations of ISO 532. I am talking about the pure tone measured equal-loudness level contours that are found in ISO 226.





(SLIDE 6) This lecture is based on 4 journal articles and 3 Internoise papers and the 5 listed on the slide are the main papers that contribute to this particular paper.

"Evaluation of Loudness-Level Weightings for Assessing the Annoyance of Environmental Noise," draft submitted to *Journal of the Acoustical Society of America*, 2001.

"Use of the proposed new ISO 226 equal-loudness level contours as a filter to assess noise annoyance," INTERNOISE 2001, *Institute of Noise Control Engineering International*, Delft, The Netherlands, 27-30 August 2001.

"A comparison between the use of loudness level weighting and loudness measures to assess environmental noise from combined sources," INTERNOISE 2000, Paper No. 101, *Institute of Noise Control Engineering International*, Nice, France, 27-30 August 2000.

"A test of proposed revisions to room noise criteria curves," *Noise Control Engineering Journal*, **48**(4), 124-129, (July/August 2000).

"Proposed revisions to room noise criteria," *Noise Control Engineering Journal*, **48**(3), 85-96, (May/June 2000).

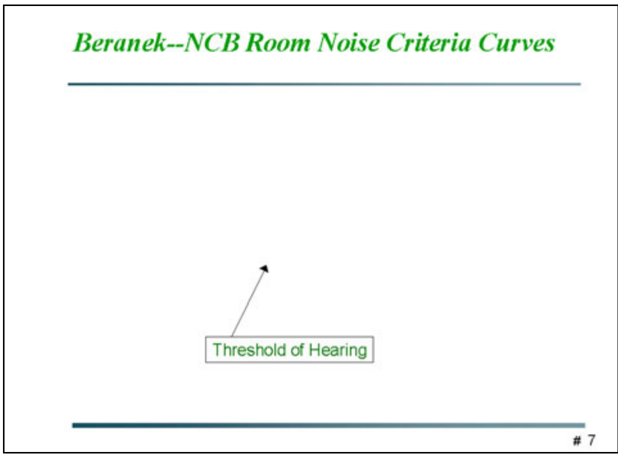
"Loudness-Level Weighting for Environmental Noise Assessment," *Acustica and Acta Acustica*, 86(1), 49-61 (January/February 2000).

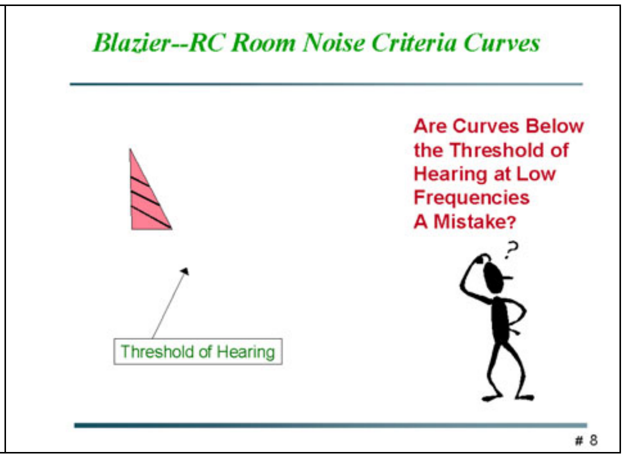
"On the use of loudness weighted sound levels to assess community noise," INTERNOISE 1999, *Institute of Noise Control Engineering International*, Ft. Lauderdale, FL, USA, 6-8 December 1999.

I will deal first with the indoor, room noise criteria issues and then with the environmental noise issues.

2. ASSESSING ROOM NOISE

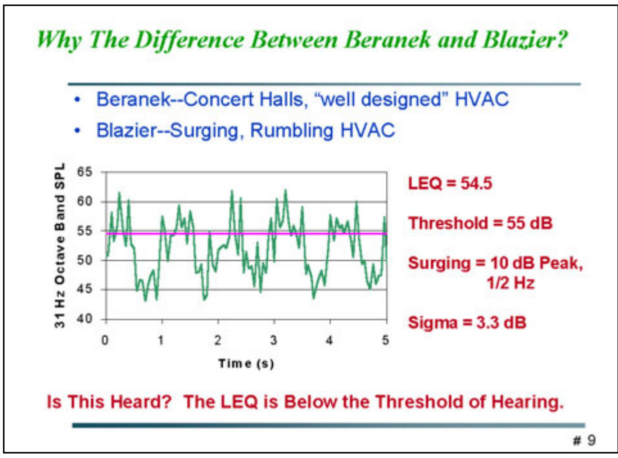
(SLIDE 7) The recent American National Standard, *Criteria for Evaluating Room Noise*, presents two sets of room noise criteria curves; one termed NCB and the other RC (ANSI, 1995). The NCB criterion curves are given in this slide. Beranek (1997) derived these curves from the characteristics of hearing to be consistent with equal loudness curves and to be consistent with subjective responses.
The RC criterion curves are given in the next SLIDE (8).They are parallel lines with a –5 dB per octave slope that goes through the stated RC value in the 1000 Hz octave band. Blazier (1981, 1997) derived these curves from experimental studies of noise in 68 offices where there were no complaints. The RC curves are designed to include the effects of slowly fluctuating low-frequency noise.

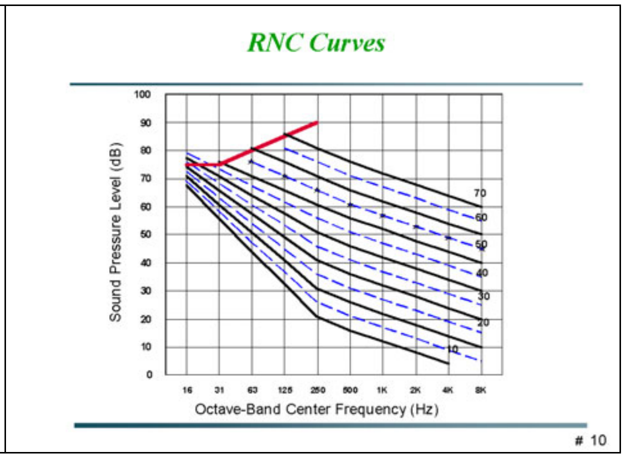




The two sets of room criterion curves each are based on data and theory, and each is correct for a specific set of situations. These two sets of criterion curves depart most markedly from one another at low frequencies and low sound levels. Also, each set has its problems. The RC curves set criteria levels that are below the threshold of hearing. This is done to protect against modern, energy efficient heating and ventilating (HVAC) systems that generate large turbulent fluctuations at low frequencies and can include fan surging with concomitant noise level surging of 10 dB or more. On the other hand, the NCB curves set criteria levels that are based on "well-behaved" HVAC systems—systems where turbulence generation is minimized and fan surging does not exist.

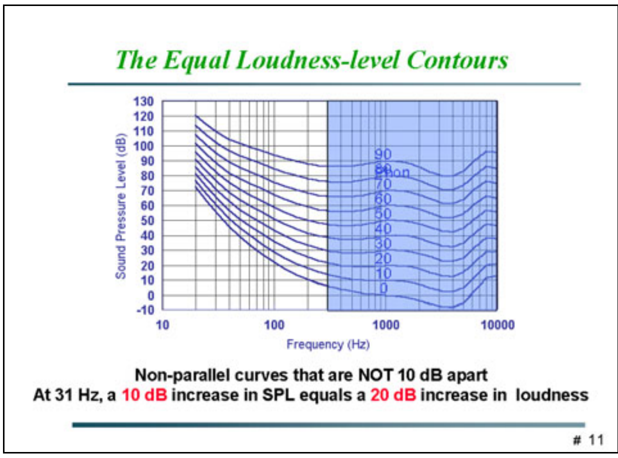
Note that the RC curves extend below the threshold of hearing. Is this a mistake? Consider sound in the 31 Hz octave band that surges between two levels that are 10 dB apart and also has considerable variation as shown in the next SLIDE (9). The LEQ is 54.5 which is just below the threshold of hearing. But this sound definitely will be heard. The sound varies slowly enough that the ear follows the changes. The loud portions of the sound that occur each half second will be heard even though the LEQ is below the threshold of hearing. In fact, as we shall see, the use of LEQ at low frequencies is not correct from a human perception standpoint. The noise criterion curves that are in widespread use today (especially in North America) are the NC, NCB and RC curves. The NC curves were developed first and are popular because measured octave-band noise levels can be plotted on the curves in the field, and a simple observation gives a result. The feature of the NC curves that is most widely supported is the so-called "tangent" method for obtaining a single rating number for the noise. With the tangent method, the highest NC curve that is touched by the measured octave-band spectrum defines the NC rating level.

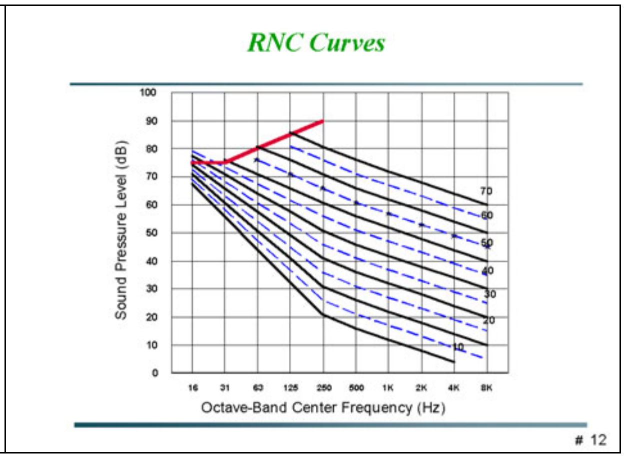




The essence of the proposal here is to evaluate the sound measured in octave bands against the Room Noise Criterion curves (RNC) illustrated in the next SLIDE (10). Since our goal, in part, is a tangency method, the following factors have been considered. Above 500 Hz the slope to the RNC curves is changed from –5 dB per octave in the RC method to –4 dB per octave because this will allow for a small tolerance at high frequencies to better accommodate to a tangency method. Between 250 and 500 Hz a –5 dB per octave slope is used since both Beranek and Blazier use this slope in this frequency range. At low frequencies the curves must approach each other in accordance with the characteristics of the auditory system.

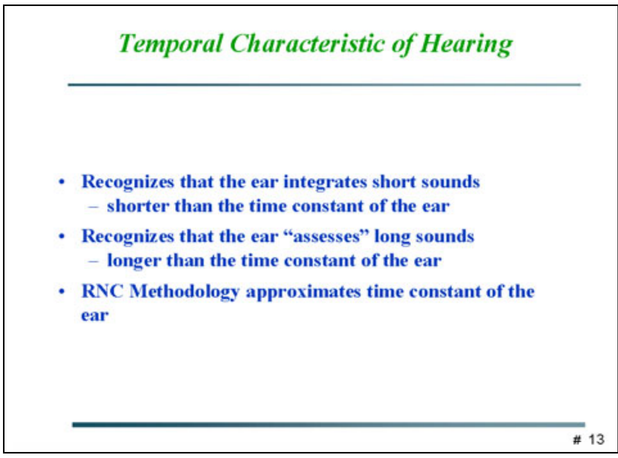
(SLIDE 11) The proposed RNC curves are such that in the 31-Hz octave band, a 10-unit change in criterion level corresponds to a 5-dB change in sound pressure level. This is to mirror the perceptual process of the ear at this frequency as given in ISO 226-1987). At 31 Hz, a 20 dB change in phon level results from 10 dB change in sound pressure level. For simplicity, in the RNC method, straight lines are used to connect the values at 31 Hz to the values at 250 Hz. These straight lines are extended to 16 Hz. Except at 16 Hz, these straight-line simplifications form a good approximation to the Beranek NCB curves.

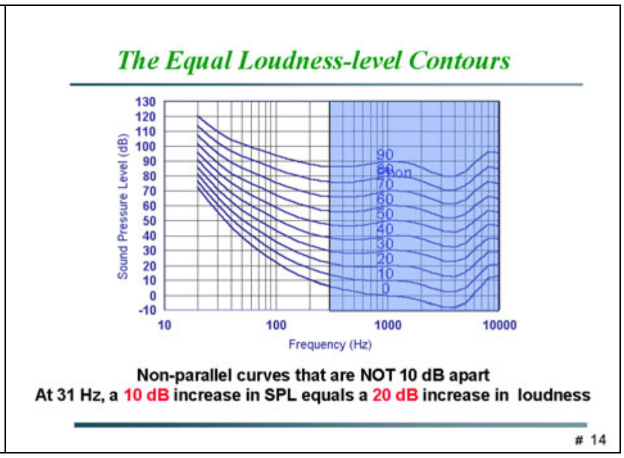




(SLIDE 12) In ANSI (1977), the speech interference level (SIL) is defined as the arithmetic average of the sound levels in the 4 octave bands centered at 500, 1000, 2000, and 4000 Hz. This SIL is used to characterize each RNC curve by equating it to the RNC curve value at 1000 Hz. Both the RC and the NCB methods (which are not tangency methods) permit sound in the low frequencies to exceed the criteria curve corresponding to the SIL of the measured sound by a specified amount. By using the proposed RNC curves as a tangency method, this feature is somewhat preserved since the SIL of the actual sound will be lower than the criteria curve for which tangency occurs.

(SLIDE 13) In addition to the spectral variation to hearing, there is also a temporal variation. Short-duration sounds are not perceived to be as loud as long-duration sounds. To be perceived with full loudness, sound must be present for a duration that is longer than the time constant of the ear. There is some general agreement that the time constant of the ear lies between 35 and 250 ms. Thus, level variations that occur over times that are long compared to 250 ms will be perceived by the auditory system as varying in loudness. But the hearing process will not perceive level variations that occur over times that are short compared to 35 ms. That is to say, short-duration variations are integrated. The *fast*-time weighting feature of a standard sound level meter should offer an approximation to the auditory integration time. Therefore, to implement the RNC concept, the method *fast*-time weights the octave band levels. These levels are then sampled at a 100 ms sample rate; a rate that is sufficiently fast for a signal that has been *fast*-time weighted.





Another facet of the auditory process must be considered; namely, it perceives noise in critical bands. Below 500 Hz, it is generally stated that critical bands are about 100 Hz wide. However, some have suggested that the lowest bands are only 50 Hz wide. If the lowest critical band is 100 Hz wide, then, roughly, sound energies in the 16, 31 and 63 Hz octave bands all combine to form the first (lowest) critical band of the ear. This is the assumption in the RNC method. Therefore, in utilizing the RNC curves, the energies of the noise in these three low-frequency octave bands must be combined.

From the next SLIDE (14) it is seen that the perception of loudness varies with frequency as well as with amplitude. At low frequencies, this variation is substantial—even within a critical band. Therefore, the sound levels in the three lowest-frequency octave bands must be amplitude weighted before they are combined together. If we take roughly the 40-Phon band as guidance, then 14 dB should be subtracted from levels in the 16 Hz octave band and 14 dB should be added to the levels in the 63 Hz octave band before they are combined on an energy basis to form the critical band centered on 31 Hz.

(SLIDE 15) We are used to calculating the LEQ of a signal. That is, we divide each interval level L_i by 10, raises the quotient to the 10th power, average these results, and take 10 times the logarithm of the average.

$$L_{eq} = 10 \log\left[(1/N)\sum_{i=1}^{N} 10^{(L_i/10)}\right] \quad (1)$$

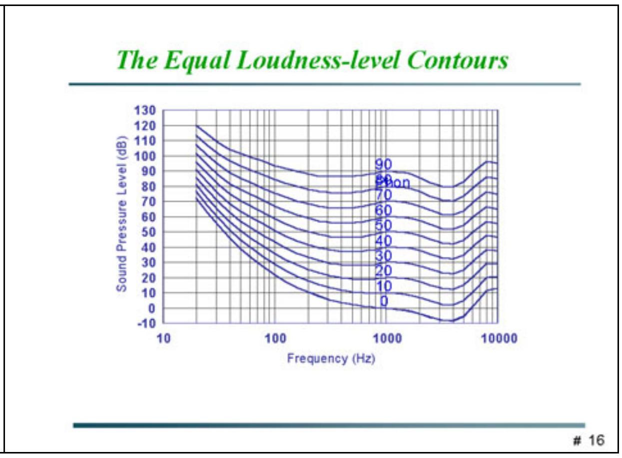
But, this does not work for fluctuating noises at low frequencies. Consider a sequence of measured noise intervals for which the levels in the 1 kHz band fluctuate as a square wave between 60 and 80 dB at a 1-Hz rate. For one-half of a second the level is 60 dB and for the next one-half second it is 80 dB. From the next SLIDE (16), we see that a sound pressure level of 60 dB at 1 kHz corresponds to a loudness level of 60 phons and 80 dB corresponds to 80 phons. The equivalent level of such a signal is about 77 dB and from the slide, the loudness level is 77 phons. The LEQ is 17 dB above the lower SPL, and the phon level also is 17 dB above the lower phon level.

Consider now the case of the same signal located in the 31 Hz octave band. Here, an SPL equal to 60 dB corresponds to a loudness level of 10 phons. The LEQ is still 77 dB, but an increase of 17 dB in LEQ at 31 Hz from 60 dB corresponds to a loudness level increase of 32 phons. Here a 10-phon increase in loudness results from approximately a 5 dB increase in SPL. The increase in loudness level at 31 Hz is about double that of the same signal level at 1 kHz.

Calculate LEQ

$$L_{eq} = 10\log\left[(1/N)\sum_{i=1}^{N} 10^{(L_i/10)}\right]$$

\# 15



(SLIDE 17) Assume that for a certain octave frequency band, 10 phon steps in the loudness level curves are caused by changes in sound level of δ dB. The equation for calculating the "true" level, $L_{eq\delta}$, taking δ into account is shown in this slide.

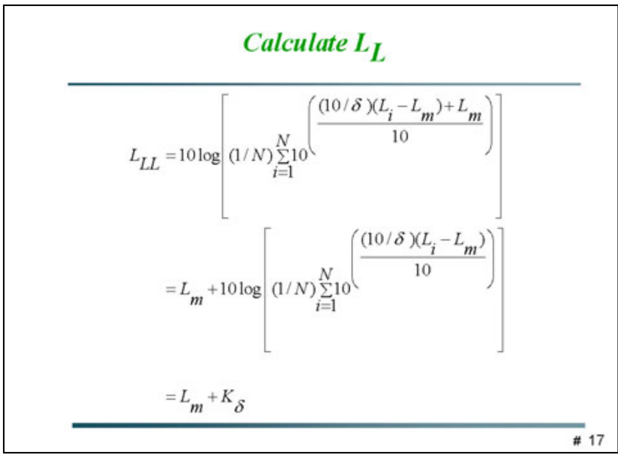
$$L_{eq\delta} = 10\log\left[(1/N)\sum_{i=1}^{N} 10^{\left(\frac{(10/\delta)(L_i - L_m) + L_m}{10}\right)}\right]$$

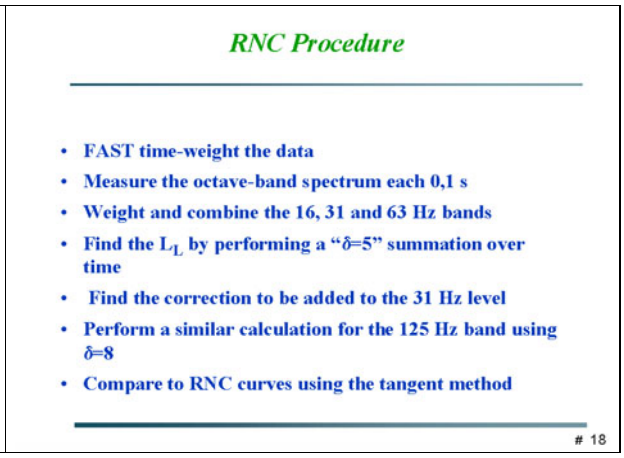
$$= L_m + 10\log\left[(1/N)\sum_{i=1}^{N} 10^{\left(\frac{(10/\delta)(L_i - L_m)}{10}\right)}\right] \qquad (2)$$

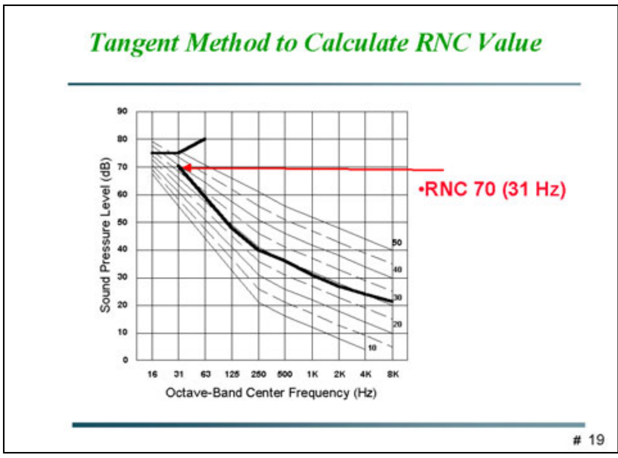
$$= L_m + K_\delta$$

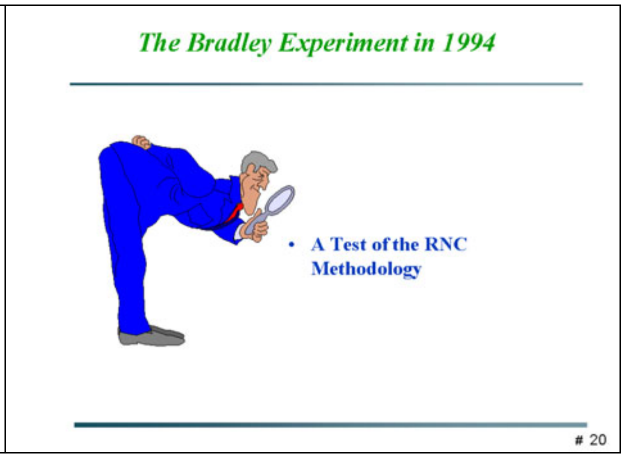
It is apparent that if δ equals 10, then this equation reduces to the equation for LEQ as it should then $L_{eq\delta}$ reduces to LEQ.

(SLIDE 18) In summary, for the development of an RNC evaluation one does the following. Each of these noise level packets is created from samples of the *fast*-time-weighted sound levels in three frequency regions, (1) the 16, 31 and 63 Hz octave bands, (2) the 125 Hz band, and (3) the 250 Hz and higher bands. For each 100 ms time sample, the three low frequency octave-band levels are combined on an energy basis after diminishing the 16 Hz band by 14 dB and increasing the 63 Hz band by 14 dB. Thus, a simple time series is created. This time series contains the level fluctuations over time in the three low-frequency octave bands—the levels and fluctuations that the hearing process is sensitive to. We are calculating a penalty or adjustment to add to the 31 Hz octave band that accounts for how the ear is hearing and perceiving the sound. This adjustment is added to the 31 Hz octave band level. The adjustment that is added to the 31 Hz octave band level is just L_L – LEQ. This adjusted 31 Hz octave band is used in the RNC calculations. We also perform a similar calculation for the 125 Hz band but with δ=8. The adjusted octave band levels are then compared to the RNC curves using a tangent method as shown in the next SLIDE (19). In this example, after adjustment, the octave band data are tangent with a highest value of 70 RNC at 31 Hz. Worked examples using this procedure can be found in the references.









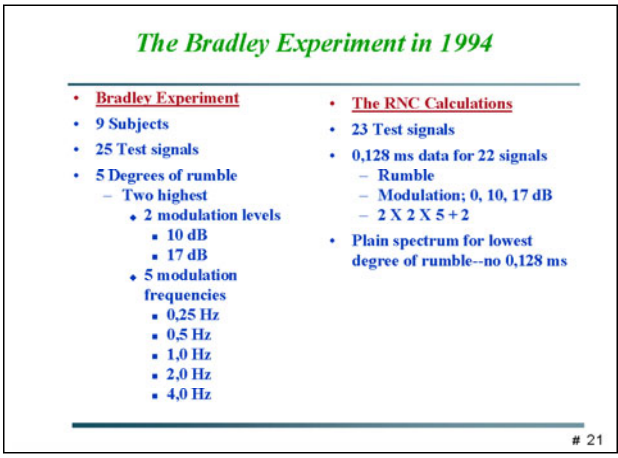
(SLIDE 20) **We Now Show A Test of The RNC Method**

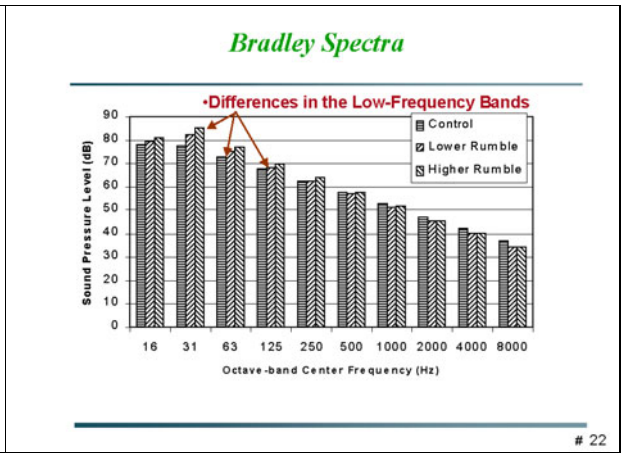
Bradley (1994) studied the annoyance generated in rooms by sounds that contain various degrees of turbulence and surging at low frequencies. He reports on an initial experiment to evaluate the additional annoyance caused by varying amounts of low-frequency rumble sounds from HVAC systems. HVAC noises were simulated with various levels of low-frequency sound and varying amounts of amplitude modulation of the low-frequency components. Nine subjects listened to the test sounds over headphones and adjusted the level of the test sounds to be equally annoying as a fixed neutral reference sound. The neutral test sound was random noise with a minus 5 dB per octave slope to the spectrum. Bradley used time-series of short-term LEQ levels to evaluate these sounds. The short-term LEQ levels were calculated each 128 ms for each one-third-octave band. Thus, these data can be used to test the RNC methodology. The 128 ms LEQ levels certainly approximate a series of *fast*-time-weighted levels, and the energies in the 16, 31, and 63 Hz octave bands can be combined according the RNC methodology. The resulting RNC levels can be compared with the psycho-acoustical evaluations provided by Bradley's subjects. We use the Bradley data to test the RNC methodology.

(SLIDE 21) The Bradley data consisted of 25 test signals. Five signals consisted of random noise with 5 degrees of rumble, the higher the rumble the higher the LEQ in the lower-frequency octave bands. Levels were increased by increasing the gain and the standard deviation to the noise. These 5 signals had no amplitude modulation to simulate fan surging. Little could be done with the 16 Hz octave band in this experiment because it used headphones and could not reproduce energy at this low frequency. Primary use was made of the 31 Hz octave band.

Bradley used the highest two rumble signals for the modulation experiment. He designated these as the “low” and “high” rumble signals. Each rumble signal was modulated at two levels, 10 and 17 dB, which he designated as “low” and “high” modulation. For each level of rumble and modulation he used 5 modulation frequencies: 0,25, 0,5, 1, 2, and 4 Hz. Thus, in the Bradley study there were 20 modulated test signals along with the 5 unmodulated test signals. Bradley’s choice of modulation frequencies centers on the important range, since, according to Blazier (2000), a modulation frequency of 1 Hz is typical of HVAC problems.

There were no analog or digital recordings of these test signals, but digital data records of the LEQ by one-third-octave band, for every 128 ms are available for all 20 modulated test signals and for the highest two unmodulated rumble test signals. Each digital record consists of 559 samples, each 128 ms in duration.



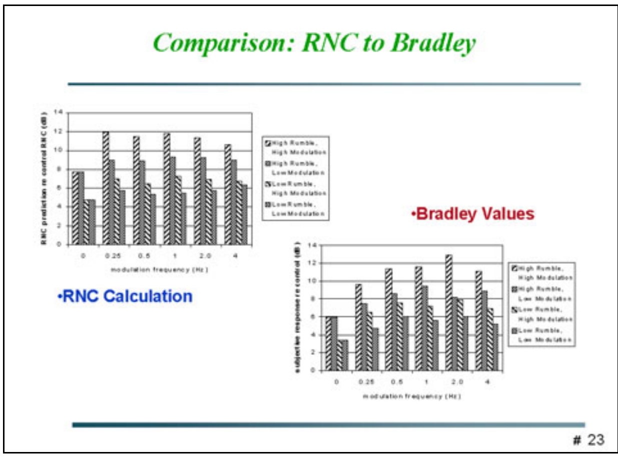


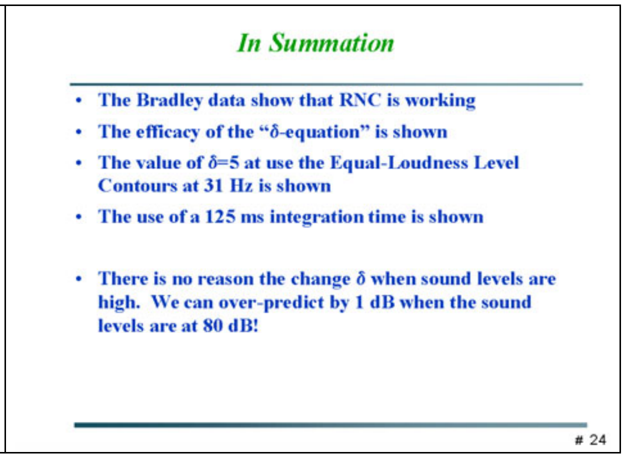
(SLIDE 22) The original two unmodulated rumble spectra used for the modulation experiment and the control signal spectra are shown here. The differences are in the low-frequency bands. Each of the 9 subjects compared separately each of the 24 test signals to the neutral, reference spectrum.
Testing of the RNC methodology using the Bradley data is straight forward. We have evaluated the RNC level for each of the 23 usable test signals, subtracted the RNC level for the reference spectrum from each of the remaining 22 test signal RNC levels, and compared these 22 differences with the corresponding 22 mean attenuator settings found by Bradley’s subjects.

The next SLIDE (23) shows the calculated RNC levels minus the reference signal RNC for the 22 Bradley test signals that were available as digital records in the form of 0,128 s time series. This slide also shows the attenuator settings found by Bradley for these test signals. Examination of the data in this slide shows that there is good correlation between the attenuator setting and the calculated RNC differences. This correlation coefficient is 0.92. More importantly, the standard deviation to the differences is only 1,1 dB. However, there is a systematic difference of 1,2 dB. If the RNC provided a perfect fit to the Bradley data, the correlation coefficient would be 1,0 the standard deviation would be 0 dB, and the systematic difference would be 0 dB. Part of the systematic difference may be due to a correction that should have been applied to the control signal. But we are unable to calculate any correction to the control signal because we no longer possess its time waveform. Any turbulence to the control signal will increase its RNC value and, thus, decrease this systematic offset of 1,2 dB.

Some of the standard deviation of 1,1 dB and the offset of 1,2 dB may result from subject bias and subject variation given that there were only 9 subjects. Most importantly, some of this variation may

be due to the assumptions inherent in the RNC procedure. First, it was assumed that δ equal to 5 dB was applicable to the 31 Hz band since, at low sound levels, the equal-loudness-level contours are spaced 5 dB apart for a change of 10 phon. In this experiment the 31 Hz octave band levels are between 80 and 90 dB. At these higher sound levels, the equal-loudness-level contours are spaced more like 6 dB apart for a change of 10 phon. Therefore, all the data were reanalyzed with various values for δ in the 31 Hz band. Repeated calculations in 0,25 increments showed that δ equal to 6.25 yielded the best fit to the Bradley data. With this value of δ, the standard deviation to the differences drops to 0,98 dB, the correlation coefficient remains at 0,92, and the offset drops to just 0,2 dB.
Both the Bradley subjective response data and the RNC calculations trend downward when the modulation rate reaches 4 Hz. This trend is consistent with the use of 125 ms as the integration time, the assumed time constant of the ear. If we had assumed that the time constant was shorter than 125 ms, say 65 ms, then the RNC-predicted differences would not reduce at 4 Hz. If we had assumed a larger value for the time constant of the ear, say 250 ms, then the RNC predicted differences would start to reduce at 2 Hz and there would be a much larger reduction at 4 Hz.



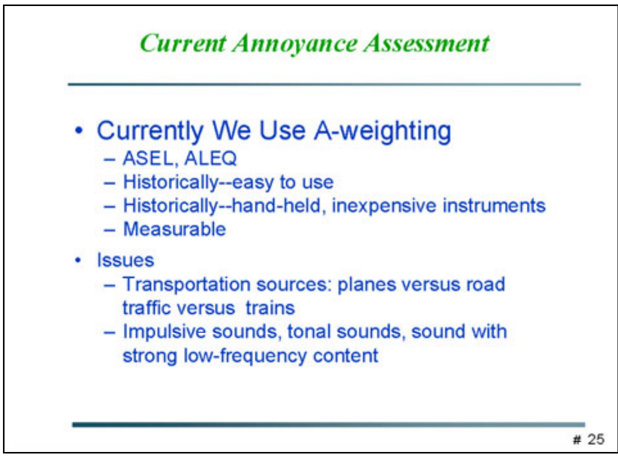


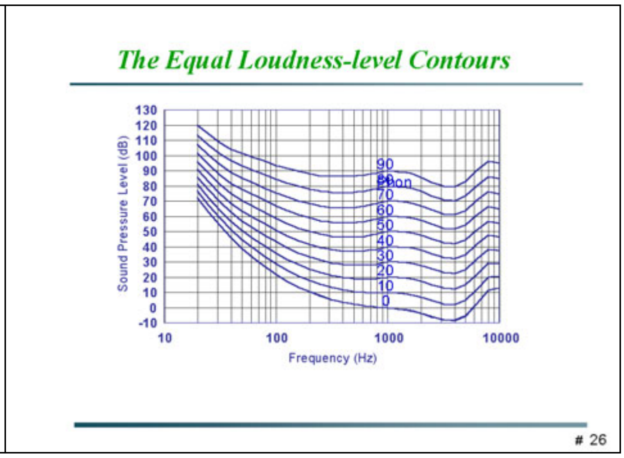
(SLIDE 24) Based on the Bradley data, the RNC procedure is working well. The efficacy of the "δ-equation" for integrating the low frequency data is clearly demonstrated. Basing the value of δ in this equation on the equal-loudness-level contours also clearly is demonstrated. Finally, the use of a 125 ms time constant to approximate the time constant of the ear has been demonstrated to be a successful approximation to the time constant of the hearing system. These three are the main features that are inherent in the RNC calculation, and all have been validated by the Bradley data.

3. COMMUNITY NOISE – We now switch to the community noise portion of this talk.

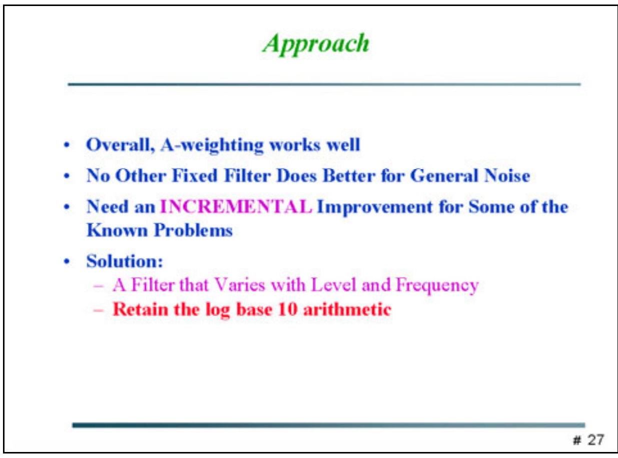
(SLIDE 25) Currently, most countries use some form of the A-weighted equivalent level (ALEQ) to assess most noises. In general, this seems to work fairly well. But, as discussed in the introduction, differences in annoyance for the same noise level are emerging for various noise sources. Historically, A-weighting is easy to use. Simple, inexpensive meters measure it in the field.
A-weighted SEL, as the fundamental building block to ALEQ, does a pretty good overall job as a noise assessment tool. The question is as follows: Is there some incremental improvement that can be made to the general ASEL concept that will better correct for some of the known deficiencies in A-weighting? The purpose of this part of this lecture is to examine one *incremental* improvement to the general ASEL concept in terms of its efficacy in ranking and rating transportation noise sources and impulsive noise sources.

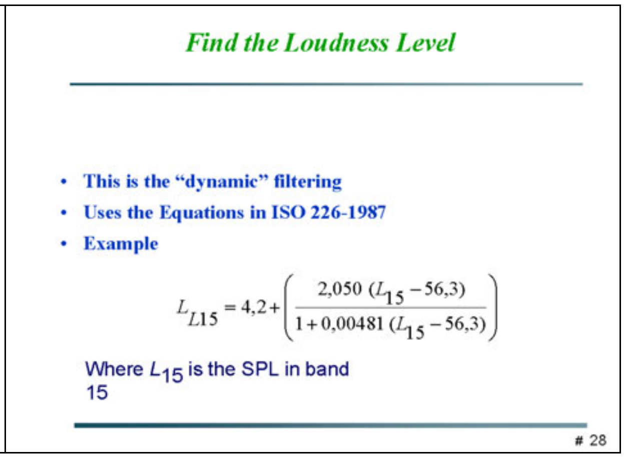
(SLIDE 26) The A-weighting curve is roughly the inverse of the 40-phon equal-loudness-level curve. But when calculating ALEQ, this simple, constant curve is applied to all sound levels as a simple function of frequency. In reality there is a family of equal-loudness-level contours that vary systematically with sound frequency and level. Why use just the inverse of the 40-phon curve as a weighting function when we can use the inverse of the entire set of equal-loudness-level contours to form a "weighting function" that changes with both frequency and level? The hypothesis to this part of this paper is that the equal-loudness level contours can be used as a dynamic weighting function that varies with frequency and level. This loudness-level weighting is an *incremental* change over A-weighting that improves the correlation with annoyance judgements. The general concept of SEL and LEQ calculated from a "filtering" is retained. For this paper, this hypothesis is tested against transportation and impulsive noise sources.





(SLIDE 27) This paper concentrates in an *incremental* change to the use of ASEL and ALEQ. It creates loudness-level weighted SEL that is designated LLSEL and loudness-level-weighted LEQ that is designated LL-LEQ. These metrics retain the log-base-10 energy summation process inherent in ASEL. In contrast, the methods of loudness per ISO 532b depart from the log-base-10 energy summation process. The methods of loudness use a log-base-2 summation process, so the methods of loudness represent a much further departure from the concepts of ASEL and ALEQ than do the concepts given in this paper where we retain the log-base 10 summation. The philosophy of this paper is that ASEL and ALEQ work fairly well. The energy addition inherent in these A-weighted measures should be retained; only an incremental improvement is required.





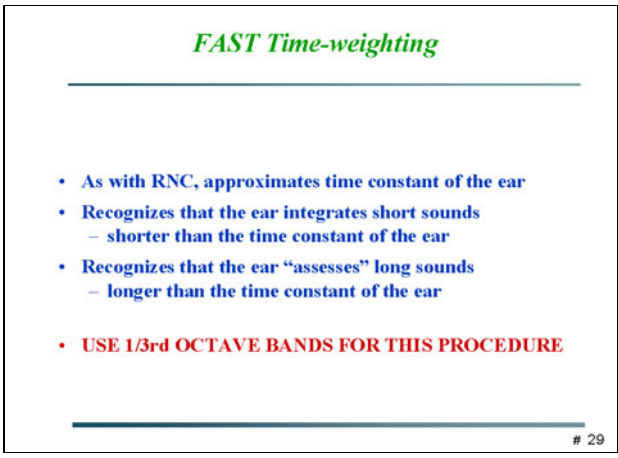
(SLIDE 28) Equal-loudness-level contours are given in functional form in ISO 226 [19]. The functions in ISO 226 correspond to one-third octave band center frequencies from 20 Hz to 12500 Hz. Conceptually, the analysis proceeds from a one-third-octave-band spectral analysis using the equal-loudness-level contours. Each one-third-octave-band sound pressure level (SPL) is assigned the phon level that corresponds to that frequency and level.

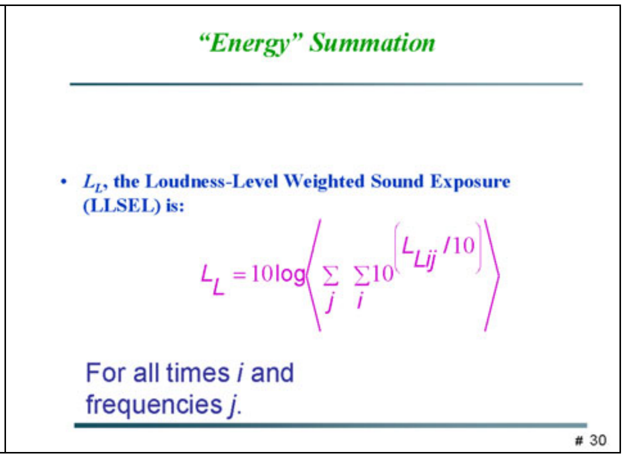
(SLIDE 29) As with the RNC procedure, the *fast*-time weighting is used to approximate the time constant of the ear. But here, one-third octave bands are used for the analysis. That is, the output of a one-third-octave-band spectrum analyzer can be set to *fast*-integration time. The spectrum is sampled every 100 ms.

(SLIDE 30) This time-series of 100 ms, one-third-octave-band spectra is used to calculate the overall time- and frequency-summed phon level, L_L, as is shown in the slide:

$$L_L = 10\log\left\langle \sum_j \sum_i 10^{\left(L_{Lij}/10\right)} \right\rangle \tag{3}$$

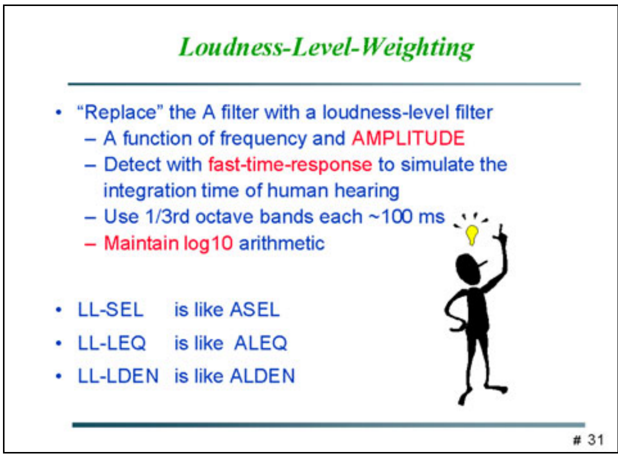
where L_{Lii} is the phon level corresponding to the *i*th one-third-octave band during the *j*th time sample.

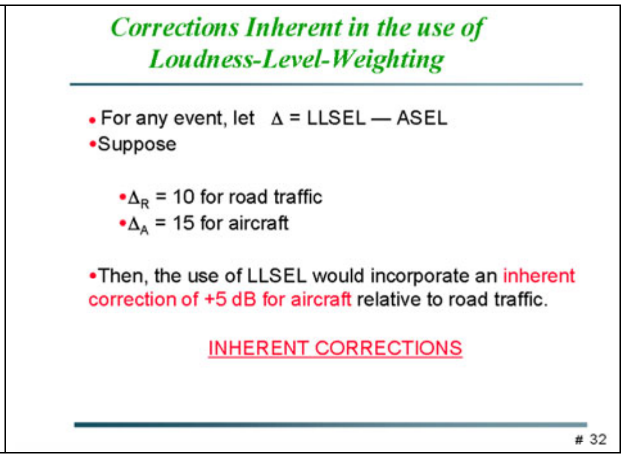




(SLIDE 31) The procedure suggested herein, sums the loudness level "energies" over time- and frequency with a time-weighting that roughly corresponds to the integration time of the ear. This energy-summation, at a properly selected rate, is integral to the efficacy of this method. If one performs the summation too slowly, then one integrates across a sound where the level is "followed" by the ear and an incorrect result may ensue. If one integrates too quickly, then unneeded processing ensues since the ear is integrating the sound more slowly.

The quantity calculated by the equation, L_L, is designated herein as the loudness-level weighted sound exposure level (LLSEL). It is similar to the A-weighted sound exposure level (ASEL) except that instead of using the A-weighting filter which varies only with frequency, LLSEL uses a dynamic filter that varies with both SPL and frequency. Moreover, the time series that is used to calculate LLSEL, is time weighted and sampled to compare roughly to the integration of sound by the ear.



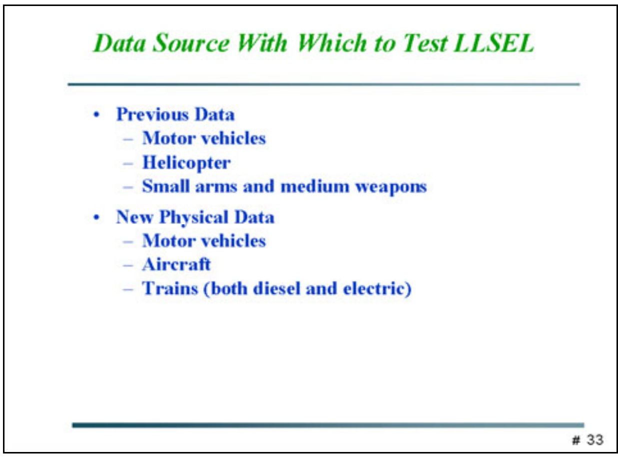


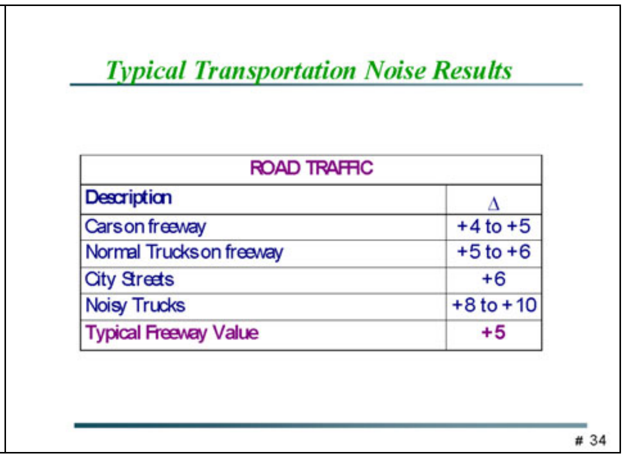
(SLIDE 32) Our purpose is to make an incremental improvement over A-weighted LEQ, an improvement that better orders and assesses different noise sources. Therefore, the parameter of interest is the difference between the LLSEL and the ASEL for various noise events. For example, the literature suggests that aircraft noise is perhaps 5 dB more annoying than road traffic noise for the same A-weighted sound level. Suppose one finds that the difference, Δ_R, between LLSEL and ASEL for motor vehicles is, on average, 10 dB, and that the Δ_A for aircraft flybys is, on average, 15 dB. Then the 5-dB adjustment that is required when using A-weighting would automatically be incorporated in the measurement if one used LLSEL, because the difference between Δ_A and Δ_R is 5 dB.

(SLIDE 33) As discussed above, the calculation of LLSEL must be performed on a 100-ms time series of *fast*-time-weighted one-third-octave-band spectra. Therefore, evaluation of the difference between LLSEL and ASEL requires the real-time or recorded time-history of the event. From previous research projects (Schomer, 1994, 1995), time-history tape recordings were available for the following:

- A variety of road vehicles driving past a fixed measurement location.
- Helicopters flying past a fixed measurement location.
- A variety of small and medium guns firing at various distances from a fixed measurement location.

These data have been augmented by real-time measurements of motor vehicles on streets and highways, aircraft taking off, aircraft landing, and electric and diesel train passbys. All of these data have been analyzed to calculate the LLSEL, the ASEL, and the difference between these two. The analysis has been performed exactly as described above. The one-third-octave-band spectral time histories were sampled every 100 ms after first detecting the one-third octave-band sound pressure levels using the *fast*-integration time of the sound level meter. The equation shown a few slides ago, with the coefficients from ISO 226, was used to find the phon level corresponding to each such one-third-octave-band sound pressure level. These phon levels were summed on an energy basis to find the LLSEL. At each time interval, the analyzer also provided the A-weighted level. This time-series of *fast*-time-weighted, A-weighted levels was summed on an energy basis to find the ASEL. These levels, so calculated, are reported in this paper.





ROAD TRAFFIC	
Description	Δ
Cars on freeway	+4 to +5
Normal Trucks on freeway	+5 to +6
City Streets	+6
Noisy Trucks	+8 to +10
Typical Freeway Value	+5

(SLIDE 34) Studies at Munster in Germany (Schomer, 1994) and studies at Aberdeen Proving Ground (abbreviated APG) in the United States (Schomer, 1995) both used the passby sound of motor vehicles as a control sound for paired-comparison testing with gunfire and other military equipment. The motor vehicles ranged from small (e.g., a van) to large (e.g., a tank transport). Supplemental measurements were made on streets and by interstate highways in Champaign, Illinois, and by an interstate highway near Seattle, Washington.

(SLIDE 35) Fixed-wing aircraft data were gathered near the "SeaTac" airport which is situated between Seattle and Tacoma, Washington, USA. Measurements were made under the flight tracks at distances between 5 and 12 km from touchdown (on landing) or start of roll (on takeoff), so, at least on landing, the distance of closest approach was about 250 to 600 m.
The APG study also included a "Huey" UH-1H helicopter that flew by the site at constant speed at an altitude of about 100 m over a heavily treed area. There were two ground distances from the study house to the flight-track projection on the ground. These were designated "near" and "far" distances.

(SLIDE 36) Train data were gathered at APG which is situated along side the train tracks that run from New York City, to Philadelphia, to Baltimore, and on to Washington DC. This is the busiest passenger train corridor in the USA having about 4 passbys per hour, and these trains are electric in contrast to diesel trains that are more common in the USA. There were also a couple of slow-moving, short diesel freight trains that were measured. There were three conditions: electric trains at constant high speed (perhaps 120 km/h), electric trains slowing for a nearby station stop, and slow, short diesel freight trains. The distance from the tracks to the measurements was about 150 m.

Aircraft Noise Results

AIRCRAFT	
Description	Δ
Jet Aircraft on Takeoff	+8
Prop-jet Aircraft on Takeoff	+9
All Aircraft on Landing	+6
"Huey" UH-1 Helicopter	+10

35

Typical Transportation Noise Results

TRAINS		
Description	Δ	Correction re Freeway
Constant, High-speed Electric (~120 km/ hr)	+4,5	—0,5
Electric, Slowing for Station Stop	+6,5	1,5
Constant, Low-speed, Short Diesel	+8	3

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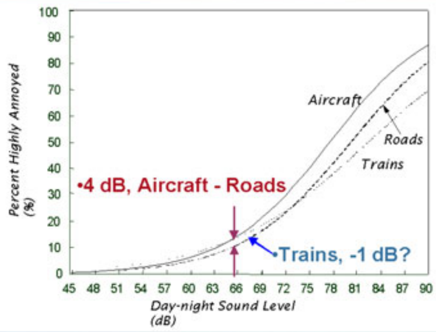
(SLIDE 37) The general relationship for Δ_i found among the transportation noise sources fits the data provided by Finegold (1994) and the general trends provided by Miedema (1995). The Finegold *et al*. and Miedema data show aircraft noise to be more annoying than road traffic noise and, in general, the Δ_A for aircraft is greater than the Δ_R for road traffic. In fact, the numerical results fit the Finegold *et. al*. data quite well. In the slide, the adjustment for aircraft relative to road traffic grows with DNL from perhaps 0 at 50 DNL to about 5 at 70 DNL. At typical community noise levels (50 to 70 DNL), the adjustment averages perhaps 2-3 dB. In this same range, there is a positive difference or no difference for trains relative to road traffic. We will call the difference zero since at higher DNLs the difference between trains and road traffic is negative. The Miedema data show greater differences as compared with the Finegold *et. al*. data, but the trends are the same. The differences in Δ_i found herein also fit the trends in the Miedema data.

Transportation Noise Source Relations: Finegold et al.



37

Highly Impulsive Noise Sources

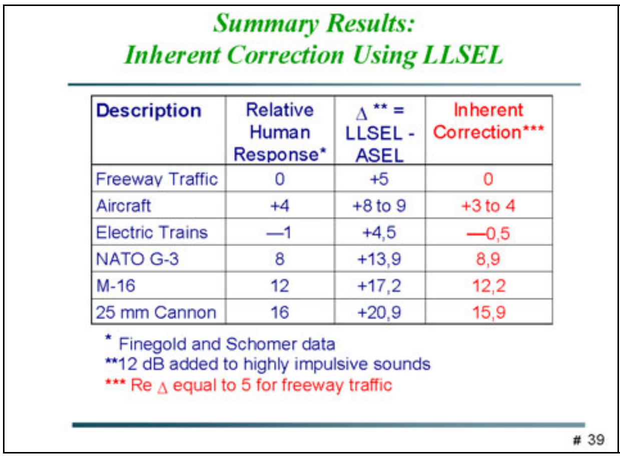
Description	Human Response Test	Δ
NATO G3 Rifle—Blank Ammunition	8	+1,9
US M-16—Service Ammunition	12	+5,2
US 25 mm Cannon (Bradley)	18	+8,9

38

(SLIDE 38) Gunfire was a part of the Munster and APG studies. In the Munster study, the NATO G-3 rifle was used firing blank ammunition; in the APG study, the M-16 rifle was used firing service ammunition. The APG test also included the Bradly Fighting Vehicle 25-mm cannon. Both the Munster and the APG studies used exactly the same test protocol and the control vehicles described above. The results indicated that penalties of about 16, 12, or 8 dB are required to properly assess the 25-mm cannon, M-16 rifle, and NATO G-3 rifle, respectively. So the penalty for the 25-mm cannon was 4 dB greater than the penalty for the M-16 rifle which in turn was 4 dB greater than the penalty for the G-3 rifle. The ASEL and LLSEL have been analyzed for a sample of these three weapons, and, on average, Δ_{GG3} equals 1,9, Δ_{GM16} equals 5,2, and Δ_{G25mm} equals 8,9.

The difference in (A-weighted) penalty between the 25-mm cannon and the M16 of 4 dB equals the difference in Δ_G between these two. Also, the (A-weighted) difference in penalty between the M-16 and the G-3 of 4 dB almost equals the difference in Δ_G of 3 dB between these two. The use of LLSEL would correctly order these three highly impulsive sources and would automatically include the correct relative numerical adjustments required when using A-weighting.

(SLIDE 39) The transportation and gunfire data can be listed in one table. For this analysis we consider traffic noise to have an A-weighted adjustment of zero when assessed using ASEL and/or ALEQ. All other sources are plotted with adjustments to their A-weighted levels that are relative to the A-weighted levels for traffic noise. For example, the NATO G3 rifle fire sound is given an adjustment of 8 dB based on Schomer (1994). All of the adjustments are listed in the slide. As noted, the values for the transportation noise source adjustments are based primarily on Finegold *et al*.

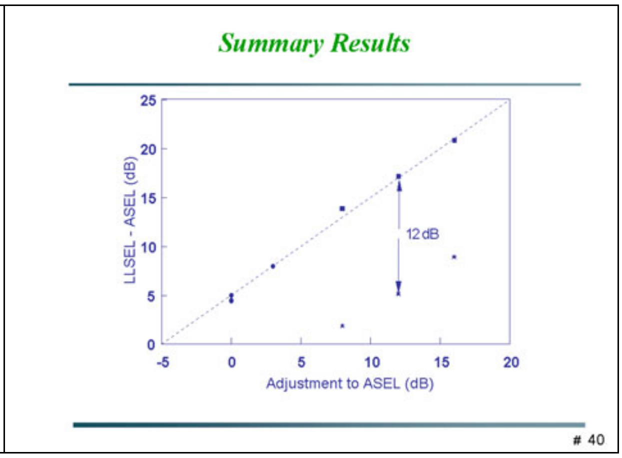


Summary Results: Inherent Correction Using LLSEL

Description	Relative Human Response*	Δ ** = LLSEL - ASEL	Inherent Correction***
Freeway Traffic	0	+5	0
Aircraft	+4	+8 to 9	+3 to 4
Electric Trains	—1	+4,5	—0,5
NATO G-3	8	+13,9	8,9
M-16	12	+17,2	12,2
25 mm Cannon	16	+20,9	15,9

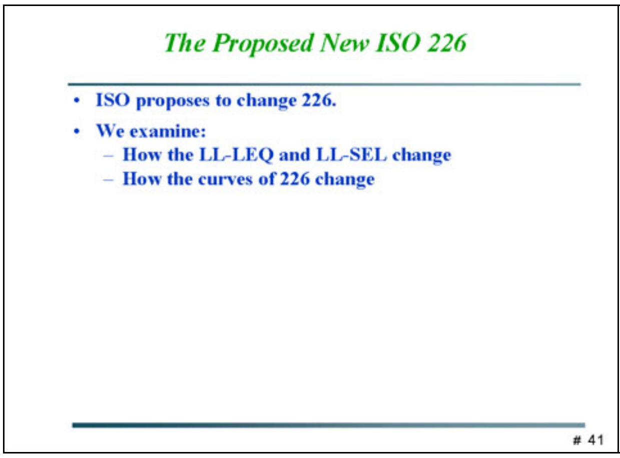
* Finegold and Schomer data
**12 dB added to highly impulsive sounds
*** Re Δ equal to 5 for freeway traffic

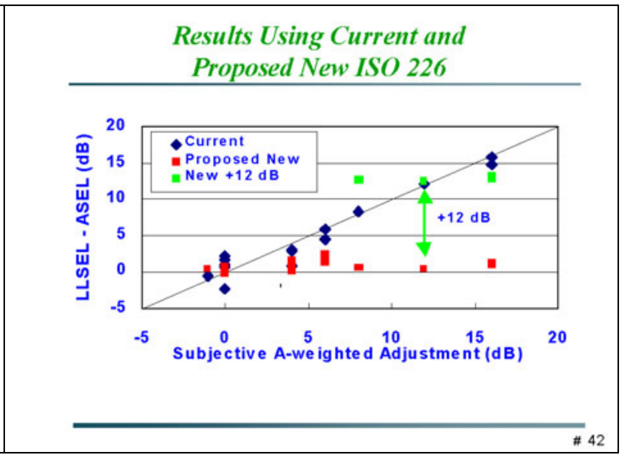
\# 39



The next SLIDE (40) plots the data from the previous slide. It contains transportation noise source data (circles), gunfire noise date (stars) and gunfire data shifted by 12 dB (squares). This slide also contains the “ideal” relation that is a dashed line with slope of one that goes through the point (0,5). The line goes through this point because our reference sound, traffic noise, had an A-weighted adjustment of 0 and a value of Δ_R equal to 5. This figure shows that if transportation noises are assessed using LLSEL, then a consistent framework is established since the data fit the ideal relation almost perfectly. There is a separate consistent framework for gunfire noise since the slope of the relation between corrections to A-weighting and Δ_G values is one. However, the relation for gunfire noise sources does not coincide with the relation for transportation noise sources. Rather, they are parallel lines that are separated by 12 dB. In order to make all 6 noise sources fit one relation it is necessary to add an adjustment of 12 phon to all calculations or measurements of the phon level for gunfire.

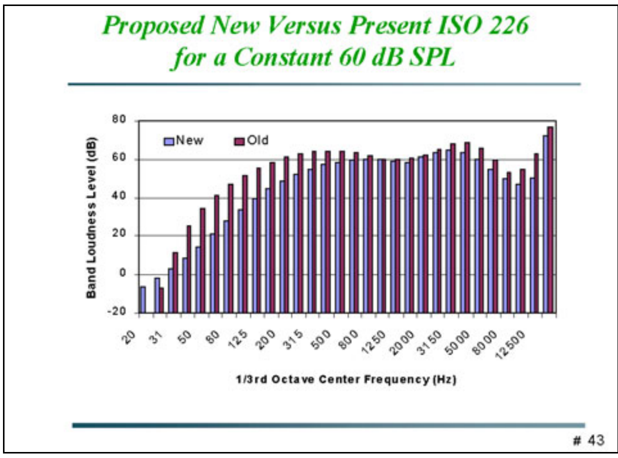
(SLIDE 41) A new version of ISO 226 has been proposed and is currently under ballot as a Draft International Standard. The following analysis compare computations of LLSEL using the current method and the proposed new method. The proposed new equal-loudness level contours give much less emphasis to the low frequencies than do the present contours.

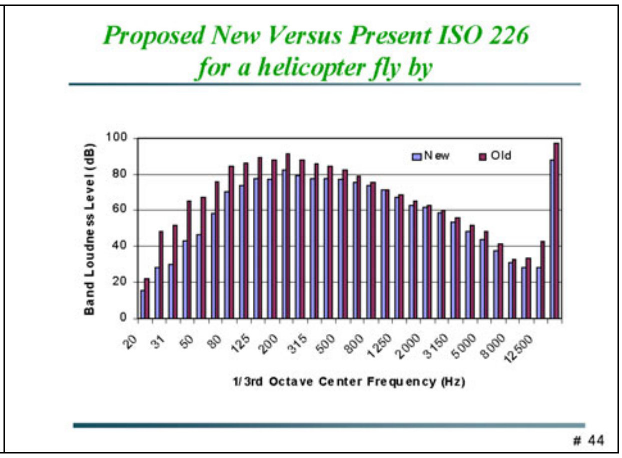




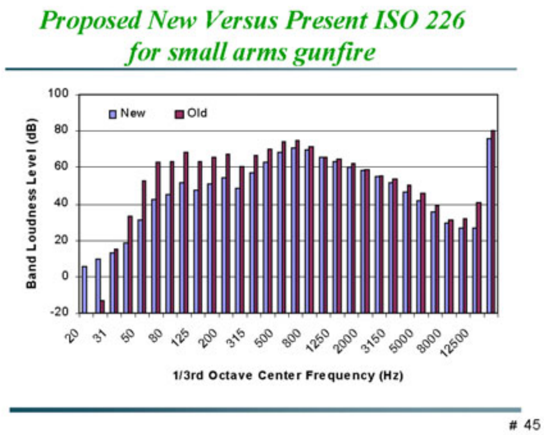
(SLIDE 42) This slide shows that calculations using the current ISO 226 (blue squares) correlate well

with the subjective A-weighted adjustments but that calculations using the newly proposed ISO 226 (red circles) virtually do not correlate with the subjective adjustments. In this slide, the gunfire data form one nearly horizontal line and the vehicle data form another nearly horizontal line. Without the 12-dB impulse noise adjustment, all of the data using the proposed ISO 226 curves forms one horizontal line that is absolutely independent of the subjective adjustments.
(SLIDE 43) The problem with the proposed ISO 226 curves is that, at the low frequencies, they yield a substantially lower phon level for the same sound pressure level. The slide compares the phon level calculated in each 1/3rd-octave band when the sound level in each band is 60 dB. The current ISO 226 curves yield substantially higher phon levels in the lower frequency bands.





(SLIDE 44) This slide shows the (energy) time-integrated phon levels in each 1/3rd-octave band using both the current and the proposed ISO 226 curves for a helicopter fly by. The current procedure shows much higher phon levels at low frequencies—40 dB higher in some bands. The overall LLSEL also is shown. This difference is more than 10 dB.



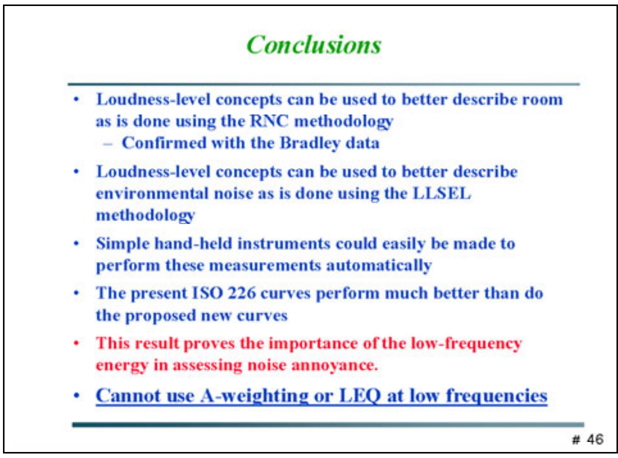
(SLIDE 45) The next slide shows a similar comparison for small arms gunfire. The previous 3 slides show that there is a big difference in the emphasis that the two sets of curves place on the low frequency energies. The current ISO 226 places a greater emphasis on the low frequency energies and, in terms of annoyance, it correlates very much better with subjective human response.

4. IN CONCLUSION

(SLIDE 46) The concepts inherent in the equal-loudness level contours can be used to effectively describe peoples' responses, indoors, to room noise and to explain the differences between criteria proposed by Beranek and Blazier. Date gathered earlier by Bradley confirm the efficacy of this method. The concepts inherent in the equal-loudness level contours can be used to effectively describe peoples' response, outdoors, to environmental noise. Loudness-level-weighted sound exposure level (LLSEL) and loudness-level-weighted equivalent level (LL-LEQ) can be used to assess environmental noise. Compared with A-weighting, loudness-level weighting will better order and assess transportation noise sources, and it will better assess sounds with strong, low-frequency content. Also, with the addition of a 12-dB adjustment, loudness-level weighting will better order and assess highly impulsive sounds.

Since Type 1, hand-held one-third-octave-band instruments are readily available at relatively low costs, it would be inexpensive to implement LLSEL and LL-LEQ and room noise criteria capabilities in these hand-held instruments. Thus, significant improvements can be made to the measurement and assessment of environmental noise without resorting to the large number of adjustments that are required when assessing sound using the A-weighting.

The LLSEL calculated using the current ISO 226 curves does a much better job of assessing combined noise sources as compared with calculations using the proposed new ISO 226 curves. The difference is the emphasis that the two sets of curves place on the low-frequency energies. The current ISO 226 places a much greater emphasis on the low frequency energies and, in terms of annoyance, it correlates very much better with subjective human response.



This result clearly shows the importance of properly assessing the contribution of the low-frequency sound energies to noise annoyance. The differences in annoyance judgements between sources appear to mainly stem from their low-frequency energy content. Any method to assess combined noise environments or indoor room noise criteria should take these differences in low-frequency energy content into account. LEQ is not a proper measurement of low frequency noise. It fails to take into account the characteristics of hearing. Sounds with LEQs below the threshold of hearing may be very audible. A modified LEQ function that takes into account the spacing of the equal-loudness-level contours is required.

(SLIDE 47) My recommendation is that we not use A-weighting to assess low-frequency noise. We must use the loudness function, probably, as given by the current ISO 226. We must use something like *fast*-time weighting to account for the time constant of hearing. These assessment procedures can all easily be built into a simple hand-held instrument that costs less than $6000. In large quantities, the cost would be much less than $6000.

5. REFERENCES

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