LOW-FREQUENCY NOISE ASSESSMENT METRICS—WHAT DO WE KNOW?

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ABSTRACT

The issue of sound quality in offices and other occupied spaces has been of continuing interest since the 1950s. Existing assessment methods do not adequately account for the low-frequency background sound (< 250 Hz) produced by operating heating, ventilating, and air-conditioning (HVAC) systems, in particular, low-frequency rumble. This paper discusses the results of ASHRAE-sponsored research in which more than 75 HVAC noise samples were collected, normalized, and categorized in terms of sound quality. The results support previous findings that a neutral curve has a slope of approximately −5 decibels (dB) per octave. There is also support for the contention that the balanced noise criterion B (NCB) curves are overly conservative in the region from 63 to 500 Hz and overly permissive below 63 Hz when compared with the room criteria (RC) curves. A modified set of room sound quality (RSQ) curves—the room sound quality (RSQ) curves—is proposed.

INTRODUCTION

In our everyday life, we are conscious of, at a minimum, maintaining or, preferably, improving our environment, both indoors and outdoors. An important aspect of this overall environmental concern is the issue of sound (acoustical) quality.

Recent and current building practice has resulted in an increase in the number and severity of low-frequency noise problems at frequencies of 250 Hz and less, mainly due to the increasing use of variable-air-volume (VAV) air-distribution systems and floor-by-floor or rooftop packaged air-handling equipment.

However, little work has been done to directly address the question of how people react to indoor noise in situations where the low-frequency background sound (< 250 Hz) is established by the operating HVAC system and, in particular, where such a system causes a dominant low-frequency rumble. The existence of rumble is clearly contary to the sound quality we wish to achieve; therefore, there is a need to define what is acceptable.

This paper describes the initial results of ASHRAE-sponsored research that sheds some light on an appropriate assessment method for low-frequency noise annoyance.

EXISTING ASSESSMENT METHODS

The issue of sound quality in offices and other occupied spaces has been of continuing interest since the 1950s and, with an increased emphasis on total sensory comfort, sound quality has recently become even more important. Various assessments of acoustical comfort in buildings have been proposed.

The noise criteria (NC) curves proposed by Beranek (1957) have been widely accepted for use in the United States both as a means of evaluating existing noise problems and also to define design goals for achieving acceptable background noise levels in various occupancies. Meanwhile, in Europe, a set of noise-rating (NR) contour curves similar to Beranek's NC curves was proposed by Kosten and Van Os (1962). Use of the NR curves has, in practice, been entirely for rating internal noise.

A noise spectrum that closely follows an NC curve does not itself give a pleasant sound but rather has a rumble characteristic and hiss. Beranek et al. (1971) therefore revised the NC curves partially to take into account the non-neutral (i.e., "rumbly" or "hissy") nature of the NC curve spectrum. This was probably the first explicit attempt to achieve an acceptable sound quality and resulted in the preferred noise criterion (PNC) curves. However, they have not been widely accepted for general use.

More recently, Beranek (1989) derived the balanced noise criterion (NCB) curves based on octave-band analysis. A major result of this revision was the extension of the curves down to the 16-Hz octave band. The NCB curves do not consider time modulation. Blazier and Ebbing (1992) have indicated that there is considerable concern about the permissiveness of the NCB contours in the 16-Hz and 31.5-Hz octave bands.

The author supports these concerns. Indeed, the low-frequency sensitivity as shown in the low-frequency noise rating (LFNR) curves (Broner 1980; Broner and Leventhall 1983) was deduced specifically because case histories indicated that curves similar to the NCB curves could still result in low-frequency annoyance.

Another approach to achieving sound quality from HVAC systems was proposed by Ebbing et al. (1978). The low-frequency energy content of HVAC noise (31.5-Hz to 250-Hz octave bands) was compared with the high-frequen-

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1994(2)

cy energy content (500-Hz to 8-kHz octave bands). The resultant "rumble evaluation chart" was the first attempt at a rumble severity assessment (i.e., of defining the rumble component of acoustical quality). The results also indicated that exceeding a "neutral" spectrum by 5 dB would result in a noise judged to be "rumbly" by most observers. This latter result became the basis of the 5-dB "rumble roof" when using the RC curves.

Blazier (1981), also considering the issue of sound quality, identified four dimensions that need to be considered in HVAC system assessment: level, spectrum balance, tonal content, and temporal fluctuations. He investigated approximately 200 background noise environments and showed that, for the 68 noise spectra whose sound levels fell within the range of 40 to 50 dBA, most of the spectrum shapes had a common characteristic—an average slope of about −5 dB/octave over a broad frequency range.

Considerations of speech communication masking criteria and of noise-induced vibration at low frequencies led to the development of the room criterion (RC) curves, which included octave bands down to 16 Hz. In 1987, the RC curves were adopted by ASHRAE as the preferred criteria in recognition of the mounting low-frequency noise problems (ASHRAE 1987; see also ASHRAE 1991).

In addition to the curves, Blazier (1981) reintroduced the concept of low-frequency imbalance (LFI). Differences of more than 30 dB in spectral energy between 31.5 Hz and 250 Hz and between 500 Hz and 8 kHz were found to result in a positive response that the HVAC noise was "rumbly." More recently, Blazier and Ebbing (1992) described a "frequency imbalance index" (FII) for an HVAC spectrum with respect to an RC curve. The use of this index permits one to determine the extent of spectrum imbalance (rumbly, neutral, or hissy) by calculation rather than by graphical solution.

At the time, Broner was conducting research on low-frequency noise annoyance in general (Broner 1978, 1979; Broner and Leventhall 1983). It was clear that the existing methods for assessment of internal noise levels did not succeed, particularly where low-frequency noise was concerned. Acceptable sound quality was not being achieved with the methods then available. The need for a modification to established indoor noise criteria to account for annoyance caused by low-frequency and/or low-level noise came from various case histories and field studies, which suggested that if the difference between the overall linear sound pressure level (SPL) and the A-weighted SPL was more than 20 dB when the A-weighted SPL is low (as is the case for HVAC systems exhibiting rumble noise), then a complaint of low-frequency noise could occur. Increased sensitivity to energy in the 30- to 50-Hz region was also found.

Therefore, Broner (1980) developed the low-frequency noise-rating (LFNR) curves based on one-third octave-band analysis (see also Broner and Leventhall 1983). Broner used a one-third octave-band approach rather than an octave-band approach because he felt that one-third octave bands provided a better assessment of acoustical quality.

Thus, the LFNR curves were the first, and so far the only, sound quality assessment curves to incorporate a one-third octave-band approach. (Note also that there is therefore a 5-dB difference between any given LFNR and RC curves.)

The LFNR curves were derived for the general evaluation of acceptable noise levels in buildings and residences due to all types of low-frequency noise sources, ranging from external sources such as gas turbines and fans to internal sources such as HVAC systems and boilers.

Broner and Leventhall (1983) also recognized the importance of temporal effects and included a 3-dB penalty for those situations where a low-frequency noise measured indoors was either "throbbing or fluctuating."

In summary, it can be seen that the NC, PNC, NR, and LFNR curves are essentially single-stage determinations in that the spectra are plotted on the criteria curves and the exceedance is judged. The RC and NCB ratings both require a two-stage process to determine the existence of rumble from an octave-band analysis and hence are more complex in use, particularly the NCB. Only the LFNR requires one-third octave-band analysis.

It is interesting to compare the various asessment methods in terms of spectral imbalance—the low-frequency imbalance (LFI) is 20 dB for the RC35 curve, 20 dB for the LFNR35 curve, 21 dB for the PNC35 curve, 26 dB for the NC35 curve, 29 dB for the NCB35 curve, and 38 dB for the NR35 curve. This illustrates the tightness of the RC and LFNR curves at low frequencies with respect to NC, NR, and NCB (see Figure 1 and Table 1).

In terms of improving the current sound quality assessment methods, it is appropriate to consider incorporating the philosophy behind the LFNR curves—a one-third octave-band (or possibly critical band) analytical approach, a low-frequency noise penalty below 80 Hz, and a rumble penalty. In addition, the speech intelligibility approach of the RC could be utilized to give a family of easy-to-use sound quality curves.

DATA COLLECTION

To get a better indication of the appropriate assessment curves to use for low-frequency noise annoyance assessment and of the variation in sound quality structure, more than 75 HVAC noise samples were collected. The majority of the samples were collected in offices and meeting rooms of various sizes. Some corridors and lobbies were also included.

For a majority of the sites visited, HVAC noise was found unacceptable by the occupants to the extent that action had been instituted to achieve a change in the existing sound quality. The majority of these HVAC noise samples thus represent *real* problem spectra and therefore provide a current insight into what people regard as unacceptable sound quality with regard to low-frequency HVAC noise.

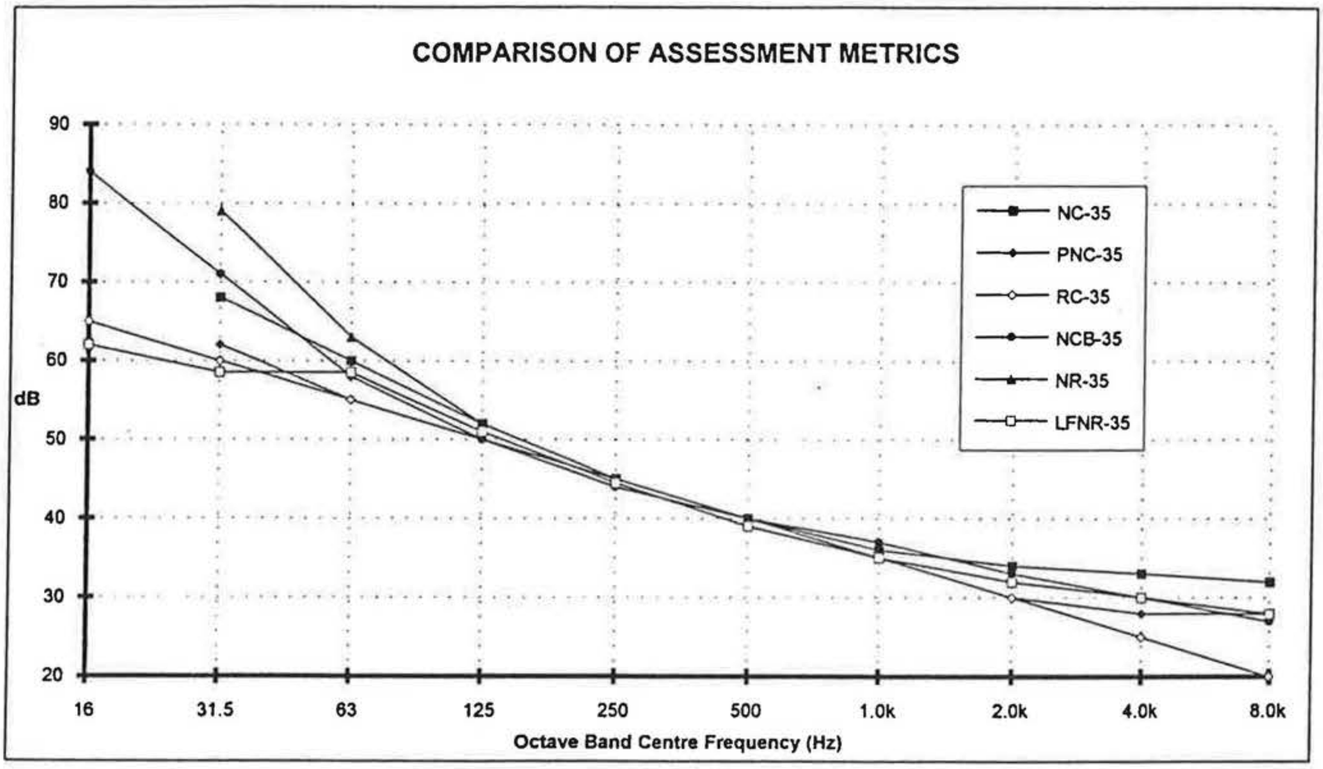

Figure 1 *A comparison of the six criterion curves, each having a rating of 35. (Note that all six curves are similar from 125 Hz to 1,000 Hz.)*

TABLE 1
Comparison of Six Criterion Curves, Each Having a Rating of 35
(Note that all six curves are similar from 125 Hz to 1000 Hz.)

Band Midfrequency (Hz)	NC-35 Curve (dB)	PNC-35 Curve (dB)	RC-35 Curve (dB)	NCB-35 Curve (dB)	NR-35 Curve (dB)	LFNR-35 Curve (dB)
16	—	—	65	84(A)	—	62
31.5	68*	62	60	71(B)	79	58.5
63	60	55	55	58	63	58.5
125	52	50	50	50	52	51
250	45	45	45	44	45	44.5
500	40	40	40	40	40	39
1000	36	35	35	37	35	35
2000	34	30	30	33	32	32
4000	33	28	25	30	30	30
8000	32	28	20	27	28	28
SIL (four-band)	36	33	32.5	35	36	34

*Extrapolated value.

The basis of the measurement system was a sound level meter and a professional DAT recorder. The sound level meter has a one-octave and a one-third-octave FFT/real-time analyzer and statistical analysis capability. It is battery operated, and data can be stored on an external 3-in. floppy disk drive for subsequent processing. The lower frequency limit is 1 Hz, while the upper frequency limit is 20 kHz. The system used a 1/2-in. ultra-low-noise microphone preamplifier with a lower limiting frequency of 0.9 Hz (3 dB down) fitted with an ultra-low-noise microphone. This system provided a dynamic range of more than 80 dB.

SPECTRAL CHARACTER

To obtain an indication of the sound quality of the noise samples at the measured site independent of level and to group the various site spectra on the basis of their sound quality structure, the author listened to each of the noise samples normalized to an approximate level of RC PSIL 40.

For this analysis, the designation "neutral" referred to spectra that had no significant spectral characteristics (i.e., they had slopes close to −5 dB/octave), while "neutral/marginal" referred to spectra that had slight deviations from the neutral category in some form (roar, whoosh, hiss).

"Rumble" referred to any spectrum that had some degree of rumble. This designation also included spectra that exhibited narrow band peaks below 50 Hz—these have a rumbly rather than a tonal characteristic. A further category of "strong rumble" was also chosen.

Sixty-five samples fell into these categories. Note that there were a number of spectra for which the rumble was significant and for which the temporal fluctuations were clearly obvious. Further analysis and listening have shown that *all* samples exhibit low-frequency temporal fluctuations to a similar extent. However, for many samples, this fluctuation is not readily apparent due to the presence of higher frequency masking noise. Thus, any assessment method *must* include some consideration of low-frequency fluctuations and spectral imbalance. Figures 2 through 5 show the average spectra obtained for each of the sound quality categories and the 95% confidence limits.

These spectra are important in that they provide a clue to "long-term" spectra that can result in low-frequency noise annoyance. They allow us to distinguish between the spectra where rumble is significant and the annoyance reaction is more or less instantaneous and those where the annoyance reaction builds up over some time period.

Figure 6 shows the resultant average spectra (derived from the 65 samples) for each sound quality category. It can be seen that the neutral curve has a slope of approximately −5 dB/octave, which is similar to that obtained by Blazier for neutral spectra. It can also be seen that, above 500 Hz, all categories of spectra have a slope of approximately −5 dB/octave. The neutral and neutral/marginal spectra would be assessed as acceptable by the RC method but all the rumble spectra would be assessed as unacceptable due to the low-frequency content. On the other hand, the NCB method would rate all as unacceptable principally due to increased sensitivity of the NCB curves in the region from 63 to 500 Hz when compared to the RC curves. Note that on an individual basis, for approximately 20% of the 65 spectra assessed, the NCB curves rated spectra as rumbly when the RC curves rated them as neutral (e.g., Figure 7).

Note also that with respect to the rumble spectra, the NCB assessment would clearly require less acoustical treatment to be instituted at low frequencies (31.5 and 16 Hz) than that required by the RC method. Beranek (1994) claims that "the fact that the RC curves do not allow as high a level in these bands (16, 31.5, and 63 Hz) is not meaningful" and that "there is no reason to limit the noise to levels so low that one cannot hear the noise." First, at very low frequencies, the sensation is not only one of hearing but also of feeling and envelopment. Second, it is clear from comparison with the average spectra shown in Figure 6 that the NCB curves are too permissive, particularly at 16 Hz and 31.5 Hz. This can also been seen on an individual basis in, for example, Figure 8. While this conclusion is based on the author's sound quality assessment categories only, the categorization has been supported by others and a similar conclusion can also be drawn from a comparison of the LFNR curves with the NCB curves.

The low-frequency sensitivity as shown in the LFNR curves (Broner and Leventhall 1983) was deduced specifically because case histories indicated that curves similar to the NCB curves could still result in low-frequency annoyance. Blazier and Ebbing (1992) have also indicated that there is considerable concern about the permissiveness of the NCB contours in the 16-Hz and 31.5-Hz octave bands.

WHERE DO WE GO?

It would appear to be appropriate to consider incorporating the philosophy behind the LFNR curves in terms of improving the current sound quality assessment methods. First, a one-third octave-band analytical approach should be incorporated. Second, the spectra for the "neutral," "neutral/marginal," and "rumble" sites (as shown in Figure 6) show a flattening below 31.5 Hz. This is consistent with the flattening of the low-frequency portion of the LFNR curves due to the apparent increased sensitivity of people in the frequency region of 30 to 50 Hz and is also level dependent. The author therefore recommends that the assessment curves be modified to incorporate such a sensitivity correction at low frequencies because an imbalance, even at lower levels and frequencies, could be a source of annoyance (compare with the LFNR).

Finally, the effect of the temporal character of the noise should be considered possible in the form of a "rumble penalty." For those situations where the imbalance in a spectrum is high and therefore the masking due to higher frequencies is lacking, it seems that the temporal modulation (fluctuation) effect would be particularly noticeable. A "penalty" depending on the spectrum imbalance could be incorporated.

A modified set of RC curves taking into account the one-third octave-band approach and a modified low-frequency sensitivity is proposed. These low-frequency room criterion (LFRC) assessment curves are shown in Figure 9. Note that with respect to criteria, due to the change to a one-third octave-band analytical format, the values are offset by 5 dB (e.g., the RSQ20 is equivalent to the RC25 criterion).

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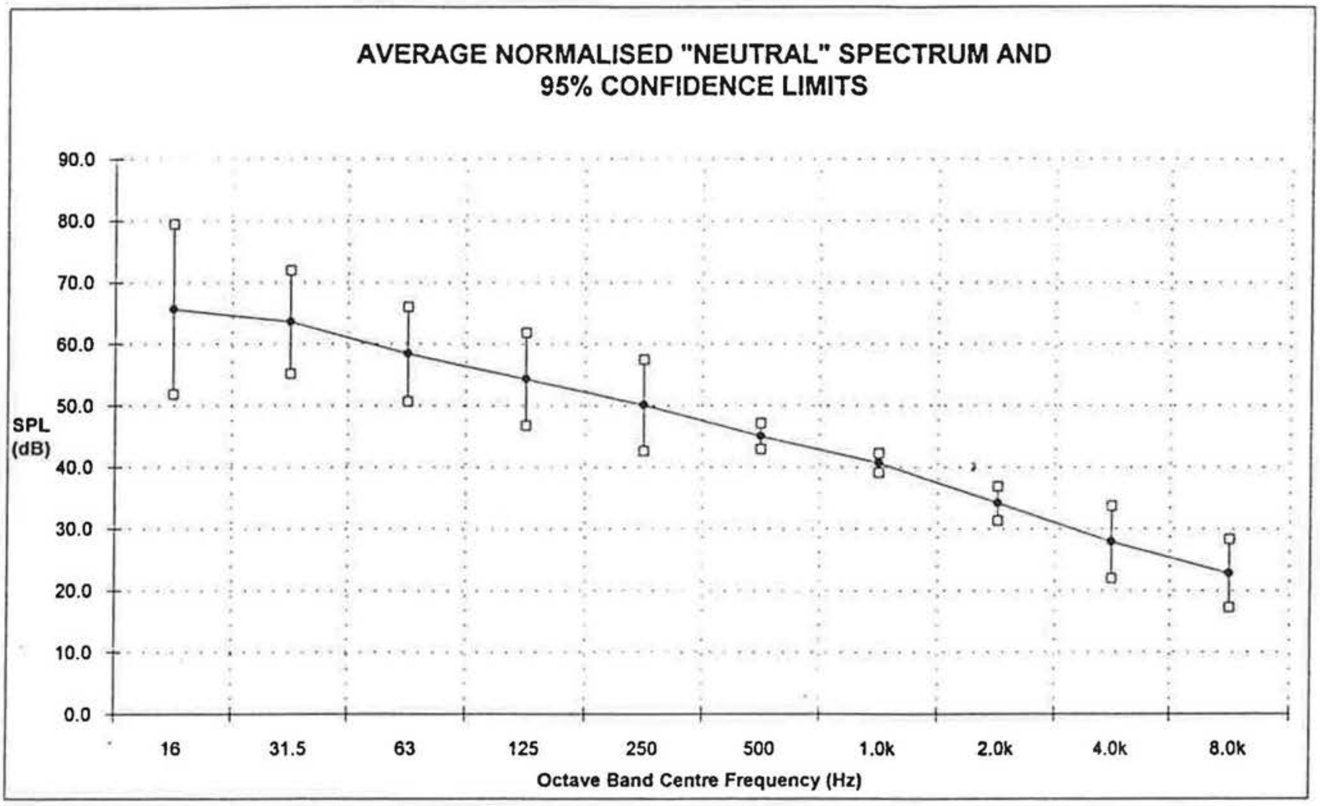

Figure 2 *Averaged, normalized "neutral" spectrum and the 95% confidence limits.*

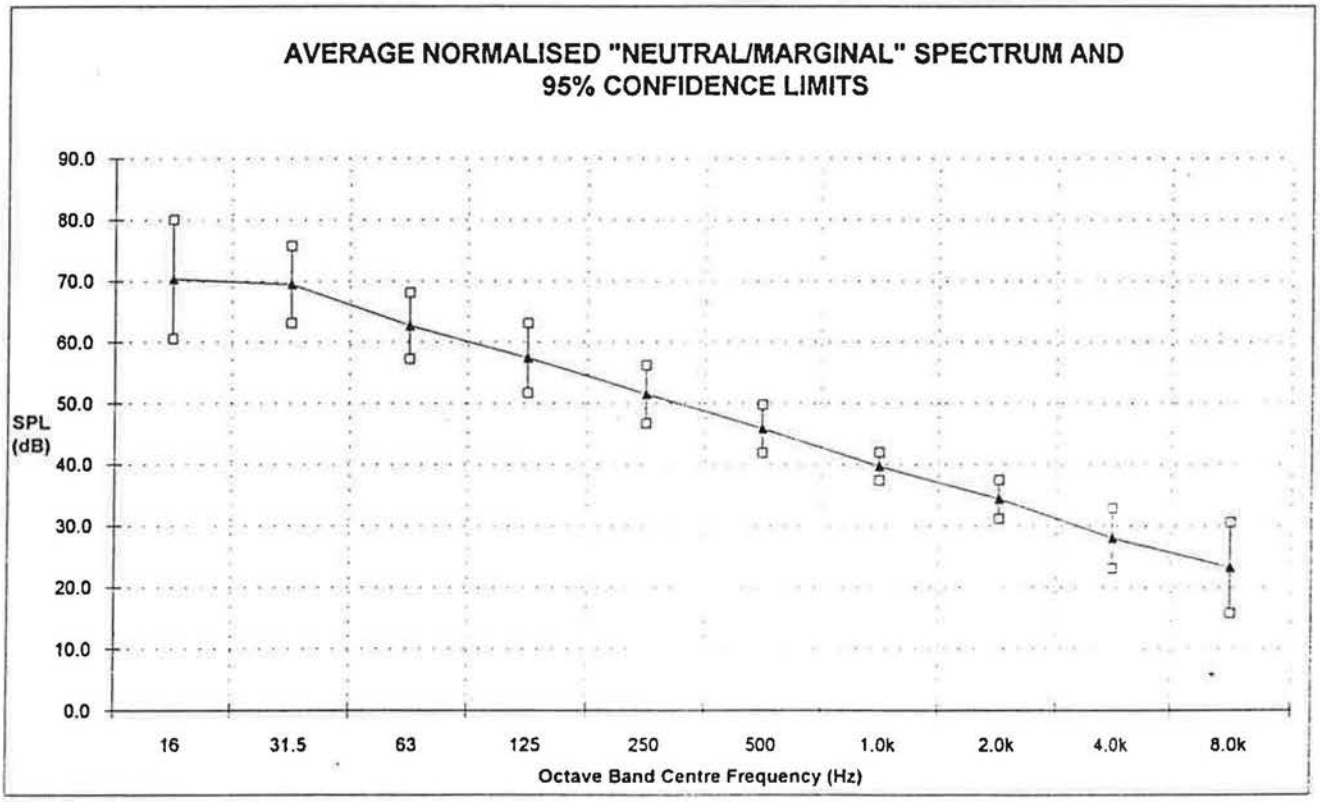

Figure 3 *Averaged, normalized "neutral/marginal" spectrum and the 95% confidence limits.*

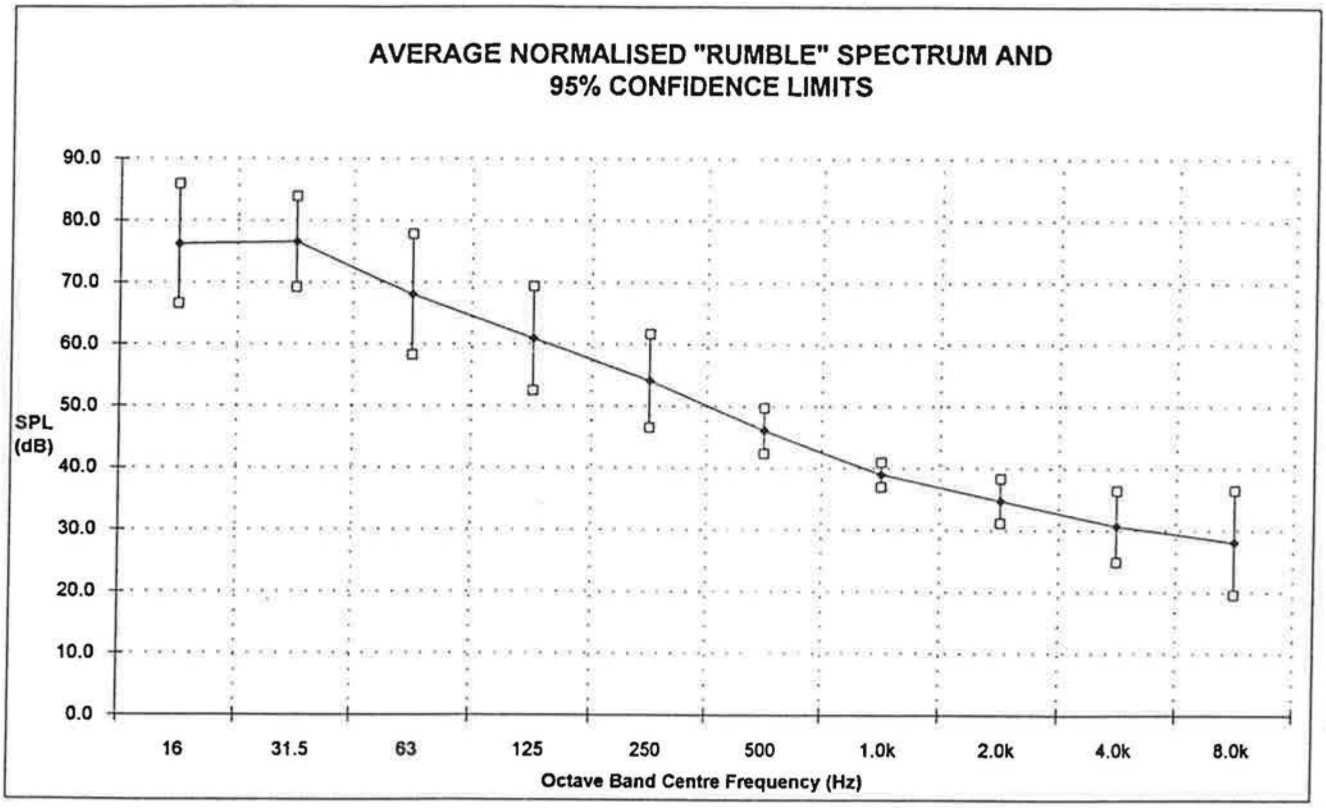

Figure 4 *Averaged, normalized "rumble" spectrum and the 95% confidence limits.*

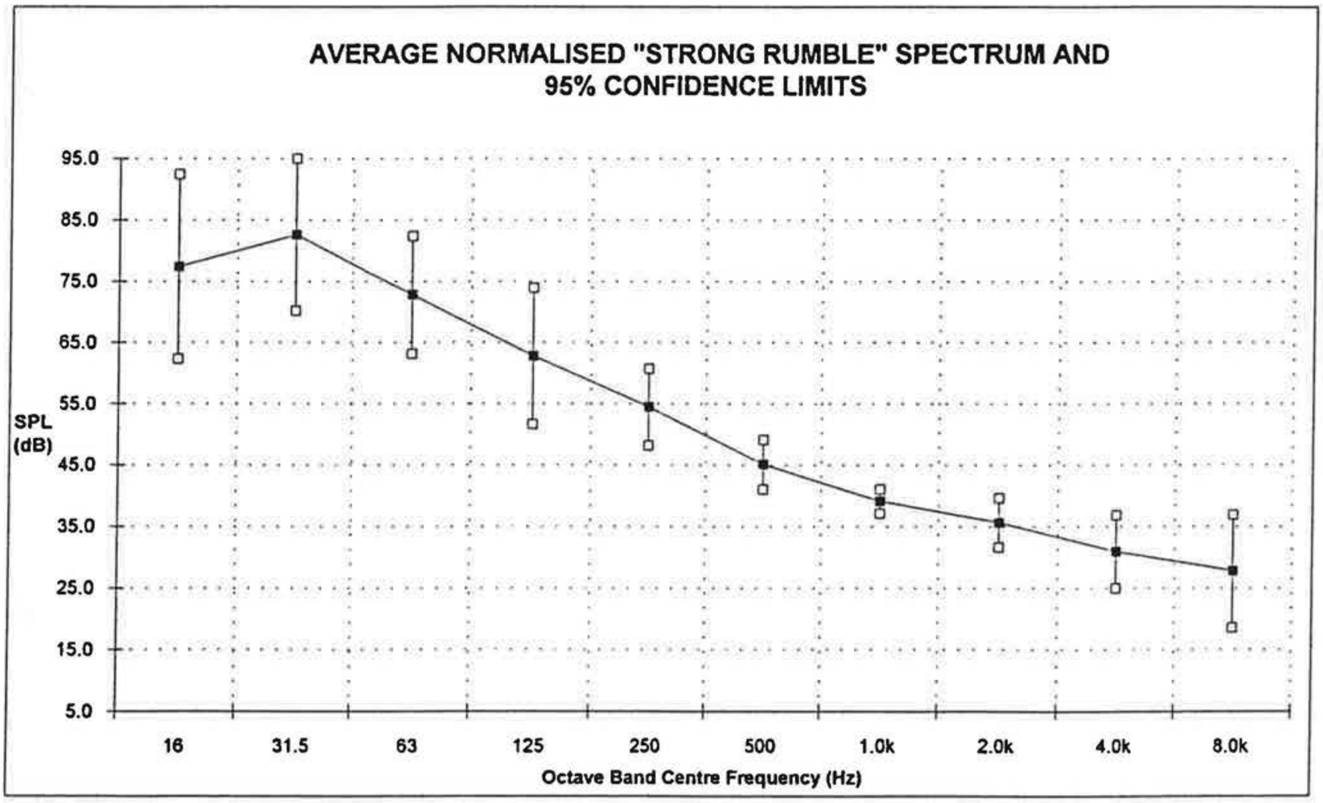

Figure 5 *Averaged, normalized "strong rumble" spectrum and the 95% confidence limits.*

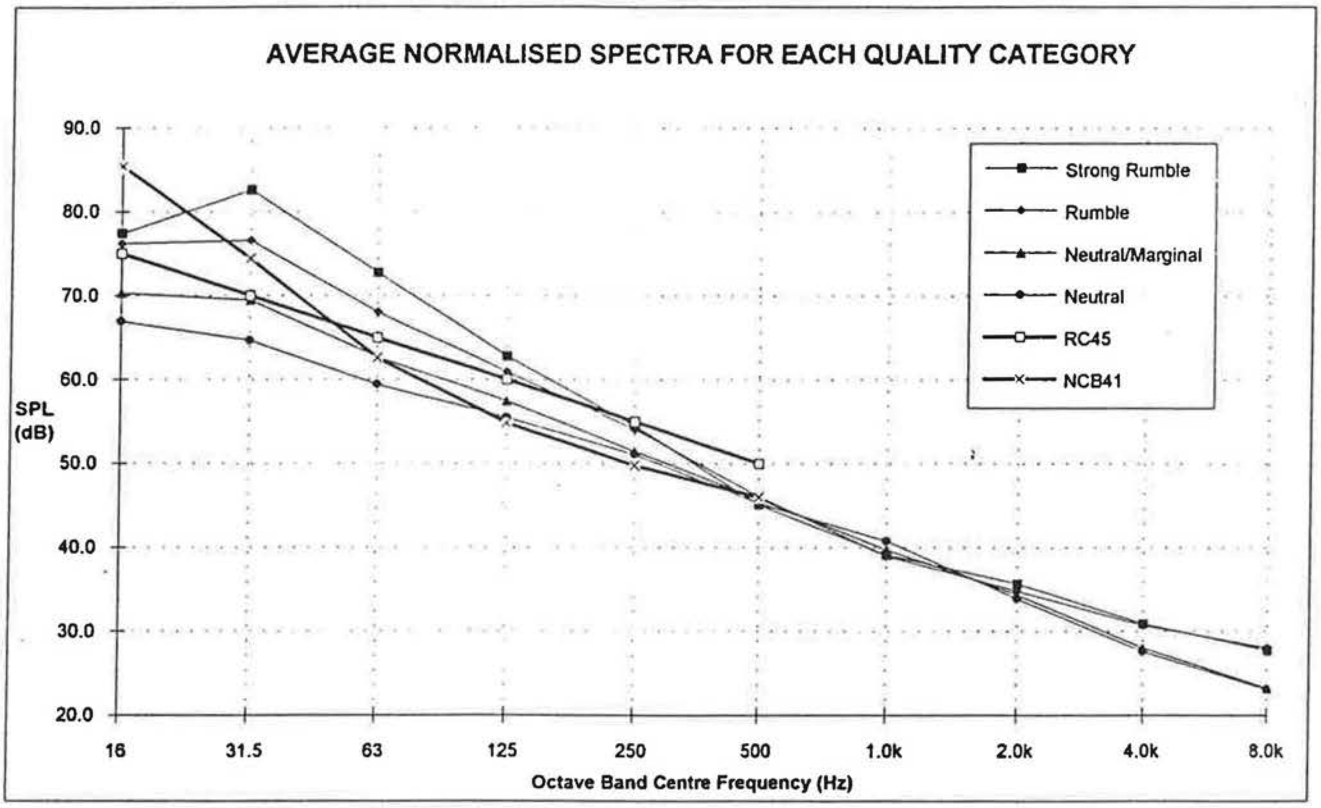

Figure 6 *Average spectra for various sound quality categories. Also shown are the relevant RC45 and NCB41 curves (the permissible low-frequency deviation curves).*

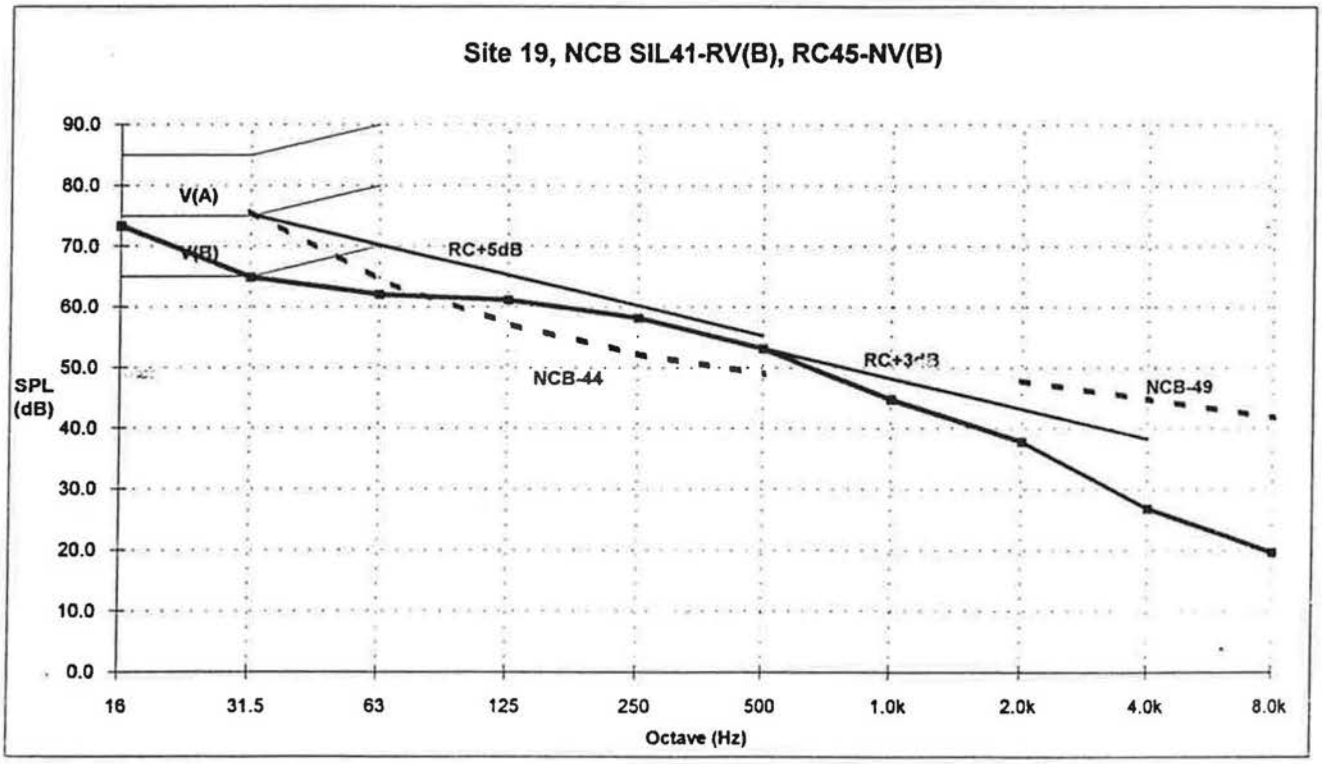

Figure 7 *A comparison of the RC vs. NCB assessments for site 19. Note that the RC assessment considers this spectrum acceptable, while the NCB assessment considers it rumbly.*

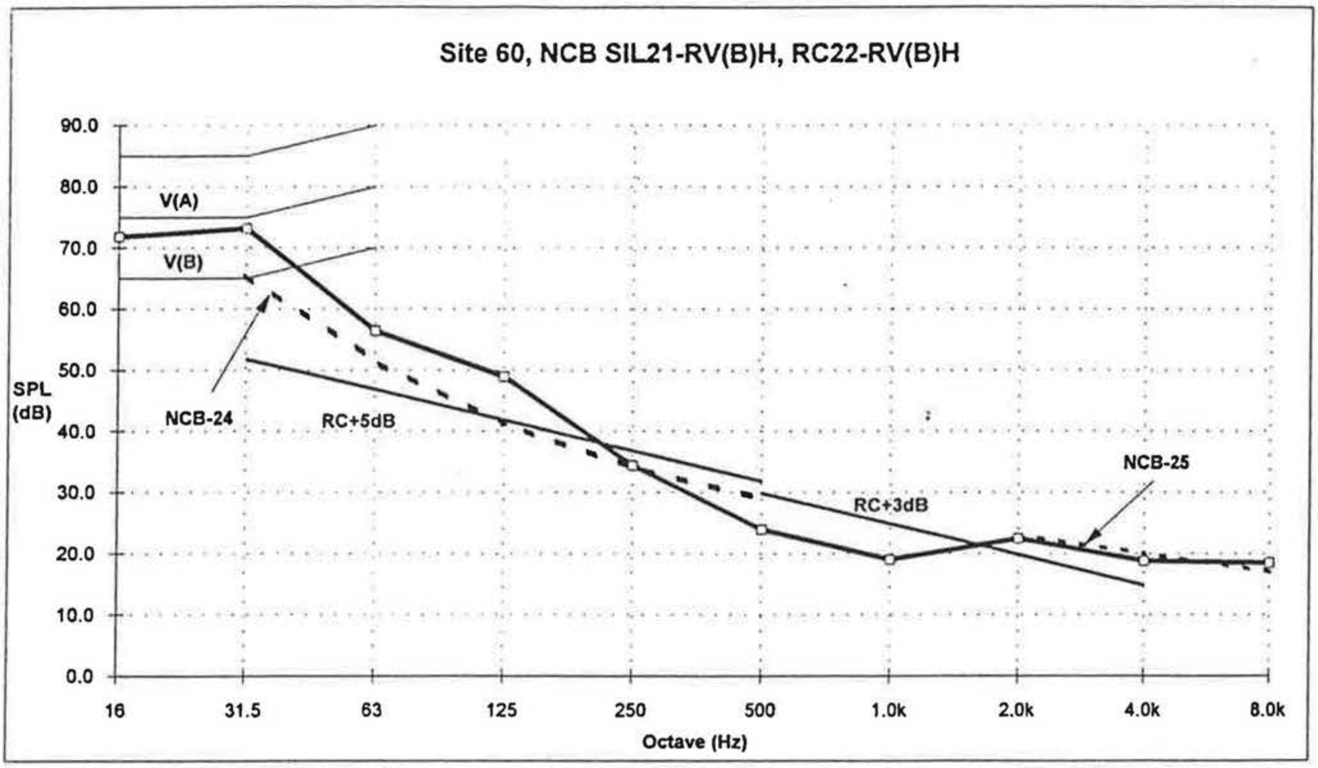

Figure 8 *A comparison of the RC vs. NCB assessments for site 60. Note the reduced requirement for low-frequency control using the NCB assessment compared to that with the RC assessment (in this case, below 125 Hz).*

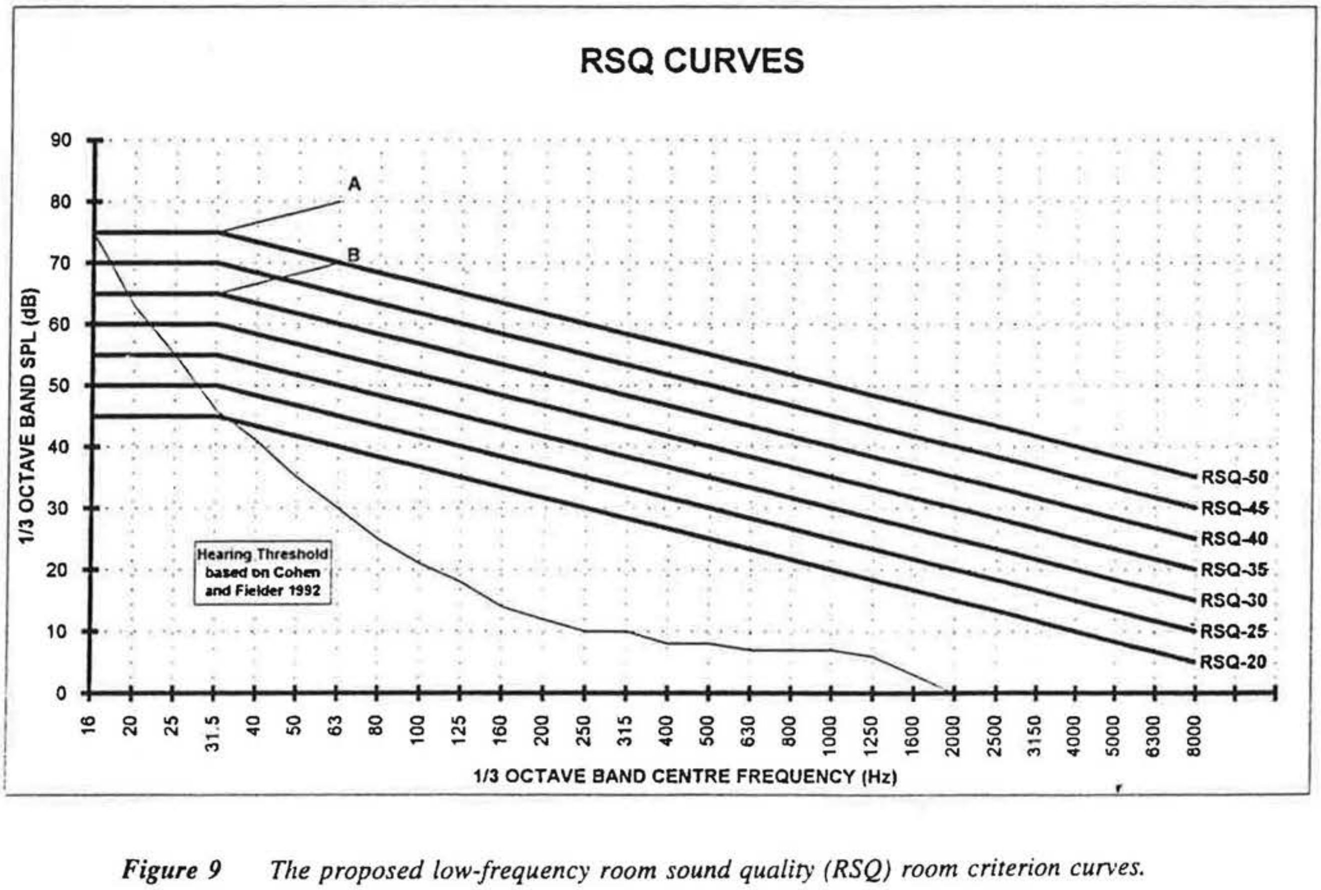

Figure 9 *The proposed low-frequency room sound quality (RSQ) room criterion curves.*