Development of Computer Program *ENMASK* for Prediction of Residual Environmental Masking-Noise Spectra, from Any of Three Independent Environmental Parameters

00-718

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ABSTRACT

Residual environmental sound can mask intrusive (unwanted) sound. It is a factor that can affect noise impacts and must be considered both in noise-impact studies and in noise-mitigation designs. Models for quantitative prediction of sensation level ("audibility") and psychological effects of intrusive noise require an input with 1/3 octave-band spectral resolution of environmental masking noise. However, the majority of published residual environmental masking-noise data are given with either octave-band frequency resolution or only single A-weighted decibel values.

A model has been developed that enables estimation of 1/3 octave-band residual environmental masking-noise spectra and relates certain environmental parameters to A-weighted sound level. This model provides a correlation among three environmental conditions: measured residual A-weighted sound-pressure level, proximity to a major roadway, and population density. Cited field-study data were used to compute the most probable 1/3 octave-band sound-pressure spectrum corresponding to any selected one of these three inputs. In turn, such spectra can be used as an input to models for prediction of noise impacts. This paper discusses specific algorithms included in the newly developed computer program *ENMASK*. In addition, the relative audibility of the environmental masking-noise spectra at different A-weighted sound levels is discussed, which is determined by using the methodology of program *ENAUDIBL*.

INTRODUCTION

Development or operational alterations at an industrial facility or on a transportation route may generate increases in noise impact ("intrusiveness") to a nearby residential community or other noise-sensitive location (e.g., school, hospital, park). The degree of modifications required to construction equipment, or operational schedules, and the severity of equipment noise-control specifications can be minimized if the masking effects of "background" (residual environmental-ambient) sounds are taken into account. In general, a newly increased intrusive sound level may be partially, or even wholly, masked by the previously existing ambient environmental noise. In order to compute this masking effect and, in turn, identify which intrusive-noise sources require attenuation, and by how much, in specific frequency ranges, it is necessary to use an appropriate residual environmental masking-noise spectrum.

Because of the relatively high cost of automated digital instrumentation, as well as the total labor and time required for its use in the field, measurements of 1/3 octave-band residual environmental masking noise may not have been made before the start of plant construction and may have to be estimated if an audibility analysis is to be made at all. A variety of field-measurement studies,

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published from 1962 to 1984, document residual A-weighted sound levels corresponding to specific residual environmental masking-noise spectra.[1-9]

These spectra vary greatly as a function of time of day and location. The use of estimated spectra (instead of measured field data) provides information required for a preliminary evaluation of the potential to control plant noise audibility and, consequently, annoyance to nearby residents. If the preliminary analysis indicates an intrusion level $(L_{I/50})^{[10-12]}$ greater than about 5 dB, preconstruction site-measured residual ambient-spectrum data are critical to determining precisely the most cost-effective plant design options that are available for achieving the necessary reduction of intrusive sound levels.

Currently, the noise-limiting A-weighted sound-level criteria adopted in the 1960s by regulatory agencies are commonly used to assess noise impacts, as well as to design the required noise-control specifications and/or operating controls. These criteria were established on the assumption that human reaction to sound is determined by the time-integrated intensity of sound, i.e., that human response is proportional to the total energy received over a period of time.[13] However, *this model does not take into account the true nature of the complex combination of physical and psychological factors that affect overall human response to sound.* Such models for detailed quantitative prediction of annoyance and/or community-complaint reactions[14] *require 1/3 octave-band spectral resolution* of both the residual masking-noise levels in the listener's location and of the intrusive sounds.

However, the majority of published residual environmental masking-noise data are given with either octave-band frequency resolution or only single A-weighted decibel values. This paper describes the application of a 1/3 octave-band synthesizing computer program, *SPECTRAN*,[15-16] in conjunction with a new program: residual <u>EN</u>vironmental <u>MASK</u>ing-noise spectra (*ENMASK*), which computes a 1/3 octave-band masking spectrum from the value of any one of three possible parametric input values, determined by known local conditions.

The staff of the Atmospheric Sciences Section of the Argonne National Laboratory (ANL) Environmental Assessment Division have been developing computational elements of an overall environmental noise-impact assessment program, *ENSOUND*, since 1996.[15-23] Each of these new component programs computes impacts by utilizing the most recently published models, from refereed journals, for computation of various physical effects on sound propagation. The *ENMASK* program will be incorporated into the *ENSOUND* model to serve, by default, for synthesis of an estimated residual environmental masking-noise spectrum, when measured data are not available.

GENERAL METHODOLOGY

On the basis of cited field-study data,[1-9] the tabular correlations shown in Table 1 are developed for three environmental conditions:

1. A-weighted sound level, "AL"

2. proximity to a major roadway, "DV"

3. population density, "PD."

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Table 1. Correlation of Vehicular-Route Proximity ("DV") and Population Density ("PD") with A-Weighted Sound Levels ("AL")[1-9]

"AL" — Residual Sound Level (dBA ref. 20 μPa)		Description of Environment	"DV" — Distance from Vehicular Traffic	"PD" — Population Density (Persons per mi²)[a]
Daytime	Nighttime			
≥ 70	≥ 70	Within heavy industrial or construction sites	N/A[b]	N/A[b]
70	65	Near heavy industrial/construction areas	N/A[b]	N/A[b]
70	60	Downtown in major cities	Within 100 m of constant heavy traffic or operating construction sites	50,000–140,000
60	55	Concentrated industrial areas	Within 100 m of constant medium traffic or 100–300 m from constant heavy traffic	14,000–50,000
55	50	Industrial areas	Within 100 m of constant light traffic or 300–600 m from constant heavy traffic	5,000–14,000
50	45	Commercial areas and concentrated urban-residential areas	Within 100 m of periodic light traffic, 100–300 m from constant light traffic, 300–600 m from constant medium traffic, or 600–1,500 m from constant heavy traffic	1,400–5,000
45	40	Urban-residential areas	100–300 m from periodic light traffic, 300–600 m from constant light traffic, or 600–1,500 m from constant medium traffic	500–1,400
40	35	Suburban-residential areas	300–600 m from periodic light traffic, or 600–1,500 m from constant light traffic	140–500
35	30	Remote suburban-residential & rural areas	600–1,500 m from periodic light traffic	50–140
30	25	Remote rural areas	1,500–6,500 m from any traffic	14–50
≤ 15[c]	≤ 20	Wilderness	6.5–24 km from any traffic	N/A[b,c]
≤ 15[c]	≤ 15[c]	Within caverns, abandoned tunnels, without water flow (≤ 3 persons near the sound level meter)	N/A[b]	N/A[b,c]

[a] Persons per km² = persons per mi² × 0.386.

[b] N/A = empirical data not found, or correlation not applicable.

[c] In an environment with a sound level of 25 dBA or less, personnel are limited to no more than 3 persons in the vicinity of the microphone.

Any one of two sets of specific algorithms are used, depending on whether AL, DV, or PD is available, to compute the most probable 1/3 octave-band residual environmental masking-noise spectrum, as encoded in the computer program *ENMASK*.

The arithmetic means of the cited octave-band spectral data, listed by A-weighted level, are tabulated in Table 2 and plotted in Figure 1. They are next transformed into energy-equivalent 1/3 octave-band spectra by use of a subroutine from the program *SPECTRAN*.[15-16] The resulting parametric set of 1/3 octave-band spectra, listed by A-weighted sound level at 5-dBA integer intervals, are presented in Table 3 and plotted in Figure 2. The 1/3 octave-band spectrum corresponding to the given value of A-weighted sound level is calculated by interpolating the set of spectra previously defined at 5-dBA intervals.

Table 2. Arithmetic Means of Cited Data for Unweighted Octave-Band Sound-Pressure Level Spectra Corresponding to Specified A-Weighted Levels of Residual Environmental Masking-Noise Spectra[1-9]

ANSI Band No. (n)	Nominal Band-Ctr. Freq. (Hz)	A-Weighted Level of Spectrum (dBA//20 μPa)										
		15	20	25	30	35	40	45	50	55	60	65
15	31.5	15.0	23.8	32.2	40.3	48.0	54.3	60.5	65.7	71.0	76.2	81.4
18	63	14.6	23.5	32.0	40.2	48.1	54.3	60.5	65.6	70.8	75.9	81.0
21	125	11.8	19.8	27.5	34.8	41.8	47.5	53.3	58.3	63.4	68.4	73.4
24	250	9.0	16.4	23.4	30.1	36.4	41.9	47.3	52.3	57.4	62.4	67.5
27	500	8.0	14.6	20.8	26.7	32.2	37.3	42.3	47.3	52.4	57.4	62.5
30	1,000	8.0	13.7	19.0	24.0	28.6	33.2	37.7	42.6	47.6	52.5	57.5
33	2,000	8.0	12.8	17.2	21.3	25.0	29.1	33.1	37.9	42.8	47.6	52.5
36	4,000	8.0	12.0	15.6	18.9	21.8	25.4	28.9	33.5	38.2	42.8	47.5
39	8,000	8.0	11.2	14.0	16.5	18.6	21.7	24.7	29.1	33.6	38.0	42.5

RESULTS

The two sets of algorithms are presented in the following section, along with a discussion of the results in the form of equivalent-rectangular (filter-amplitude-response) bandwidth (ERB) sensation levels.[23]

A-Weighted Sound Level (AL) as a Function of Distance from a Vehicular-Traffic Roadway (DV)

The relationship between the distance from a vehicular-traffic roadway (DV) and residual A-weighted sound-pressure level (AL) was developed by using the *median* values of distance and associated A-weighted sound levels listed in Table 1. A-weighted sound-pressure level is a function of both distance from a roadway and the level of traffic volume. Thus, representative

Figure 1. Plots of Data Listed in Table 2; Unweighted Octave-Band Sound-Pressure Level Spectra Corresponding to Specified A-Weighted Levels of Residual Environmental Masking-Noise.[1-9]
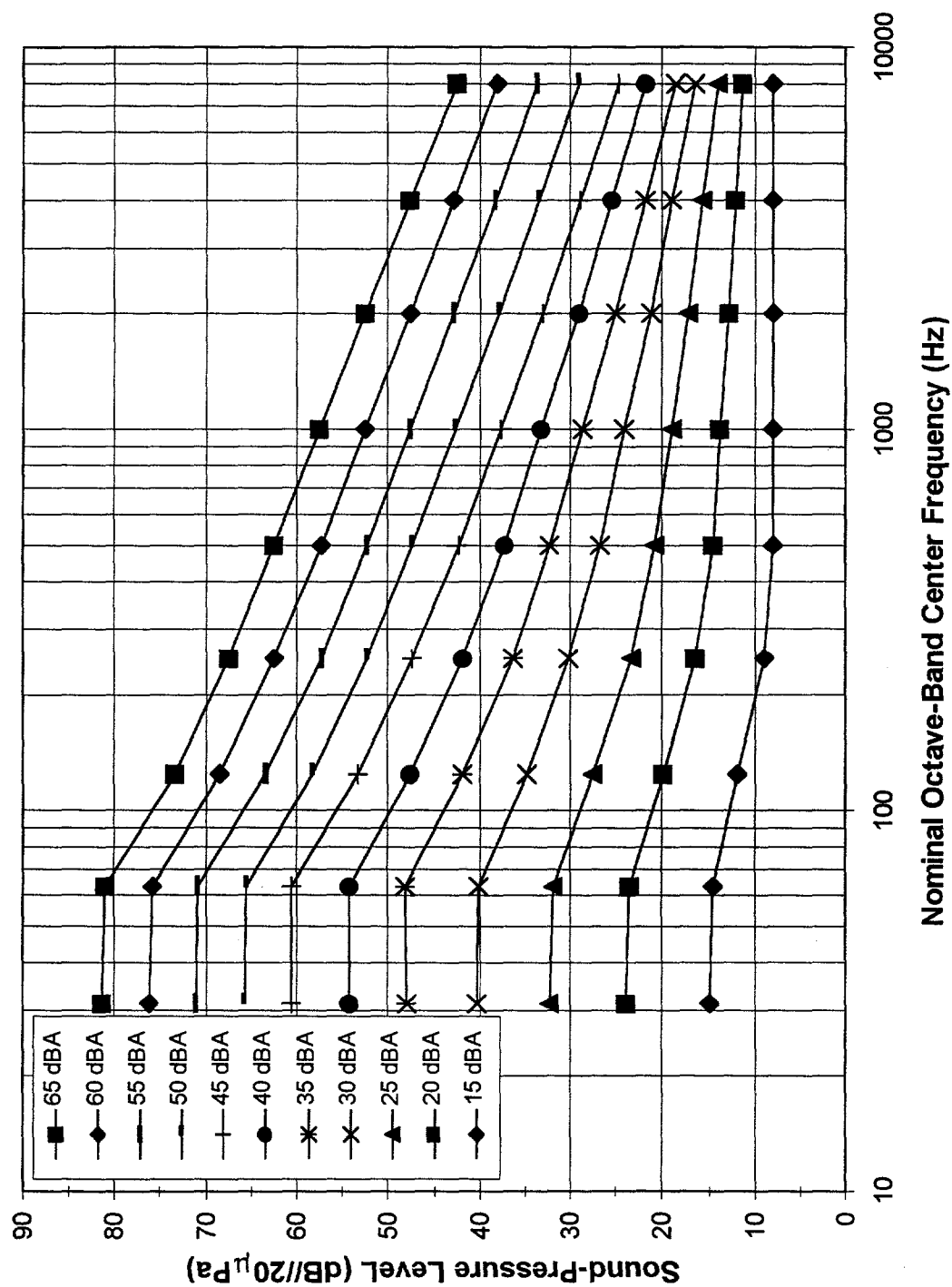
Table 3. Synthesis (from Data Listed in Table 2) of Unweighted 1/3 Octave-Band Sound-Pressure Level Spectra Corresponding to Specified A-Weighted Levels of Residual Environmental Masking-Noise Spectra

ANSI Band No. (n)	Nominal Band-Ctr. Freq. (Hz)	A-Weighted Level of Spectrum (dBA//20 μPa)										
		15	20	25	30	35	40	45	50	55	60	65
14	25	10.3	19.0	27.3	35.3	42.9	49.2	55.4	60.7	66.0	71.2	76.5
15	31.5	10.2	19.0	27.4	35.5	43.2	49.5	55.7	61.0	66.2	71.4	76.6
16	40	10.2	19.1	27.6	35.7	43.5	49.8	56.0	61.2	66.4	71.6	76.8
17	50	10.2	19.1	27.7	35.9	43.8	50.1	56.3	61.5	66.6	71.8	76.9
18	63	10.1	19.2	27.8	36.1	44.2	50.4	56.6	61.8	66.9	72.0	77.1
19	80	9.1	17.7	26.0	33.9	41.5	47.6	53.7	58.7	63.8	68.9	74.0
20	100	8.0	16.3	24.2	31.7	38.9	44.8	50.7	55.7	60.8	65.8	70.8
21	125	6.9	14.9	22.4	29.6	36.3	42.0	47.7	52.7	57.7	62.7	67.7
22	160	5.9	13.7	21.0	28.1	34.7	40.3	45.9	50.9	55.9	60.9	65.9
23	200	4.9	12.5	19.7	26.6	33.0	38.5	44.1	49.1	54.1	59.1	64.2
24	250	4.0	11.4	18.4	25.1	31.3	36.8	42.3	47.3	52.3	57.3	62.4
25	315	3.7	10.8	17.5	24.0	30.0	35.3	40.6	45.6	50.7	55.7	60.8
26	500	3.4	10.3	16.7	22.9	28.6	33.8	39.0	44.0	49.0	54.1	59.2
27	500	3.1	9.7	15.9	21.8	27.2	32.3	37.3	42.4	47.4	52.4	57.5
28	630	3.2	9.5	15.3	20.9	26.1	31.0	35.8	40.8	45.8	50.8	55.9
29	800	3.2	9.2	14.8	20.0	24.9	29.6	34.3	39.2	44.2	49.1	54.2
30	1,000	3.2	8.9	14.2	19.2	23.7	28.3	32.8	37.7	42.6	47.5	52.5
31	1,250	3.2	8.6	13.6	18.3	22.5	26.9	31.2	36.1	41.0	45.9	50.9
32	1,600	3.2	8.3	13.0	17.4	21.3	25.5	29.7	34.5	39.4	44.2	49.2
33	2,000	3.2	8.0	12.4	16.4	20.1	24.1	28.1	33.0	37.8	42.6	47.5
34	2,500	3.2	7.7	11.9	15.7	19.0	22.9	26.8	31.5	36.3	41.0	45.9
35	3,150	3.2	7.5	11.3	14.9	18.0	21.7	25.4	30.1	34.7	39.4	44.2
36	4,000	3.2	7.2	10.8	14.1	16.9	20.5	24.0	28.6	33.2	37.8	42.5
37	5,000	3.2	7.0	10.3	13.3	15.9	19.2	22.6	27.1	31.7	36.2	40.9
38	6,300	3.2	6.7	9.7	12.5	14.8	18.0	21.2	25.7	30.1	34.6	39.2
39	8,000	3.2	6.4	9.2	11.7	13.7	16.8	19.8	24.2	28.6	33.0	37.5
40	10,000	3.2	6.2	8.7	10.9	12.7	15.5	18.4	22.7	27.1	31.4	35.9

Figure 2. Plots of Data Listed in Table 3; Unweighted 1/3 Octave-Band Sound-Pressure Level Spectra Corresponding to Specified A-Weighted Levels of Residual Environmental Masking-Noise.[15]
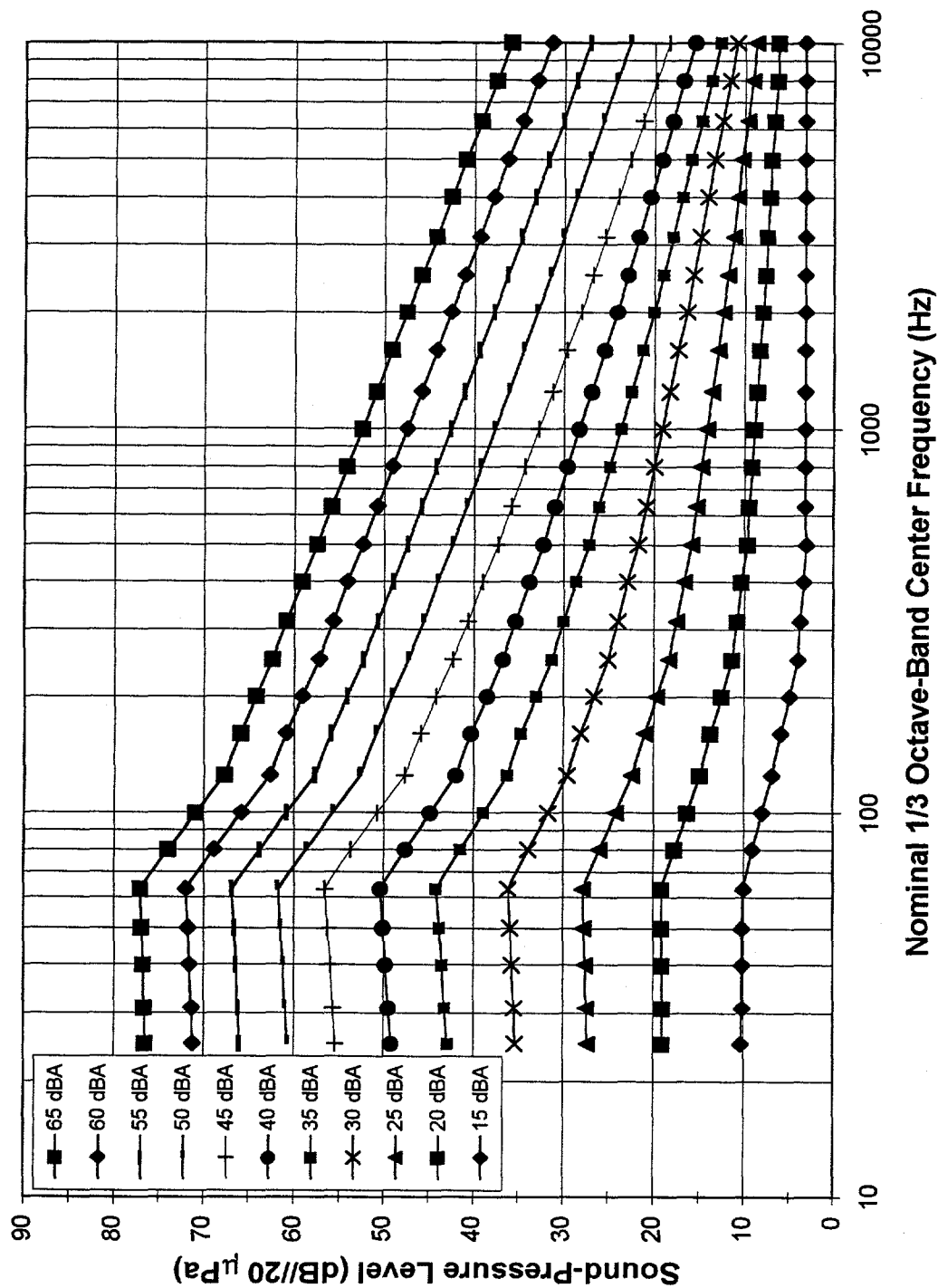
daytime A-weighted sound levels were first estimated by using the following regression formulas for periodic light traffic:

For DV in meters (DVM), $50 \le DVM \le 4,000$:

$$AL = -4.7475 \times \ln(DVM) + 69.026 \quad (dBA \; ref. \; 20 \; \mu Pa)$$

For DV in feet (DVE), $164 \le DVE \le 13,123$:

$$AL = -4.7475 \times \ln(DVE) + 74.667 \quad (dBA \; ref. \; 20 \; \mu Pa)$$

Then A-weighted sound levels for other levels of traffic volume and/or nighttime levels can be obtained by adjustment as presented in Table 4.

Table 4. Adjustment Values for Estimating A-Weighted Sound Level ("AL") in Terms of the Level of Traffic Volume and Daytime or Nighttime Conditions[a]

| Level of Traffic Volume | "DVM" – Distance from Vehicle Traffic (m)[b] | | | |
| | 50–1,000 | | 1,000–4,000 | |
	Daytime	Nighttime	Daytime	Nighttime
Constant Heavy	+15	+10	+15(4000 – DVM)/3000	+15(4000 – DVM)/3000 – 5
Constant Medium	+10	+5	+10(4000 – DVM)/3000	+10(4000 – DVM)/3000 – 5
Constant Light	+5	0	+5(4000 – DVM)/3000	+5(4000 – DVM)/3000 – 5
Periodic Light	0	–5	0	–5

[a] First, estimate the A-weighted sound level ("AL") by using the formulas for the daytime periodic light traffic volume:

For DV in meters (DVM), $50 \le DVM \le 4,000$:

$$AL = -4.7475 \times \ln(DVM) + 69.026 \quad (dBA \; ref. \; 20 \; \mu Pa)$$

For DV in feet (DVE), $164 \le DVE \le 13,123$:

$$AL = -4.7475 \times \ln(DVE) + 74.667 \quad (dBA \; ref. \; 20 \; \mu Pa)$$

Then, apply the adjustment values above in the table to arrive at the sound level for the condition of interest.

[b] ft = 0.3048 m.

A-Weighted Sound Level (AL) as a Function of Population Density (PD)

The relationship between population density (PD) and residual A-weighted sound-pressure level (AL) was developed by using the *median* values of population density and associated A-weighted sound levels listed in Table 1. Regression formulas representative of the daytime A-weighted sound levels were as follows:

For PD in persons per square kilometer (PDM), $50 \leq PD \leq 140,000$:

$$AL = 4.7146 \times \ln(PDM) + 17.421 \quad (\text{dBA ref. } 20 \text{ } \mu Pa)$$

For PD in persons per square mile (PDE):

$$AL = 4.7146 \times \ln(PDE) + 12.936 \quad (\text{dBA ref. } 20 \text{ } \mu Pa)$$

A-weighted sound levels representative of nighttime conditions can be obtained by subtracting 5 dB from the value estimated by using the above formulas.

DISCUSSION

Human hearing detects a sound when the sound-pressure level exceeds a "threshold" level, which varies with frequency. The commonly used term "audibility" is ANSI-standardized as the *sensation level*.[24] These levels are normalized to hearing-threshold levels, i.e. (sensation level) = (sound-pressure level of a source) minus (hearing-threshold level). When plotted as a function of ERB of frequency, sensation levels can provide a visual indication of which frequency ranges contain the most audible portions of the total sound spectrum.[23] Broadband sounds, having frequency components randomly distributed and lacking any prominent discrete tones (PDTs), characteristic of most natural sounds, are most effectively analyzed by their ERB sensation-level spectra.

A useful alternative presentation of these typical masking-noise spectra can be synthesized and presented as sensation levels plotted vs. the ERB scale. A general procedure for determination of such audibility plots is presented in detail in a complementary paper in this series describing development of the computer program *ENAUDIBL*.[23]

The spectral data, calculated by the cited paper[23] methodology, are plotted in Figure 3. The hearing-threshold characteristic used to calculate sensation level should be adjusted for age (presbycusis), gender, and hearing-detection efficiency (acuity) expressed as a statistical exceedance level, i.e., the percent of the population having higher threshold levels. However, for brevity and simplicity, adjustments of the threshold for gender and statistical level of acuity were not made for the data presented in Figure 3, i.e., the minimum-audible free-field threshold-of-hearing data used in Figure 3 are a median of values for otologically normal 18-year-old males and females.[27]

Figure 3 illustrates that maximum audibility of typical residual environmental noise spectra, for A-weighted environmental noise levels above about 35 dBA, will occur at frequencies in a range of about 100 to 1,000 Hz (ERB numbers 4 through 16). At A-weighted levels below 30 dBA, a greater audibility occurs in a frequency range of about 2,000 to 5,000 Hz (ERB numbers 21 through 29).

Figure 3. Sensation Levels vs. ERB Number.
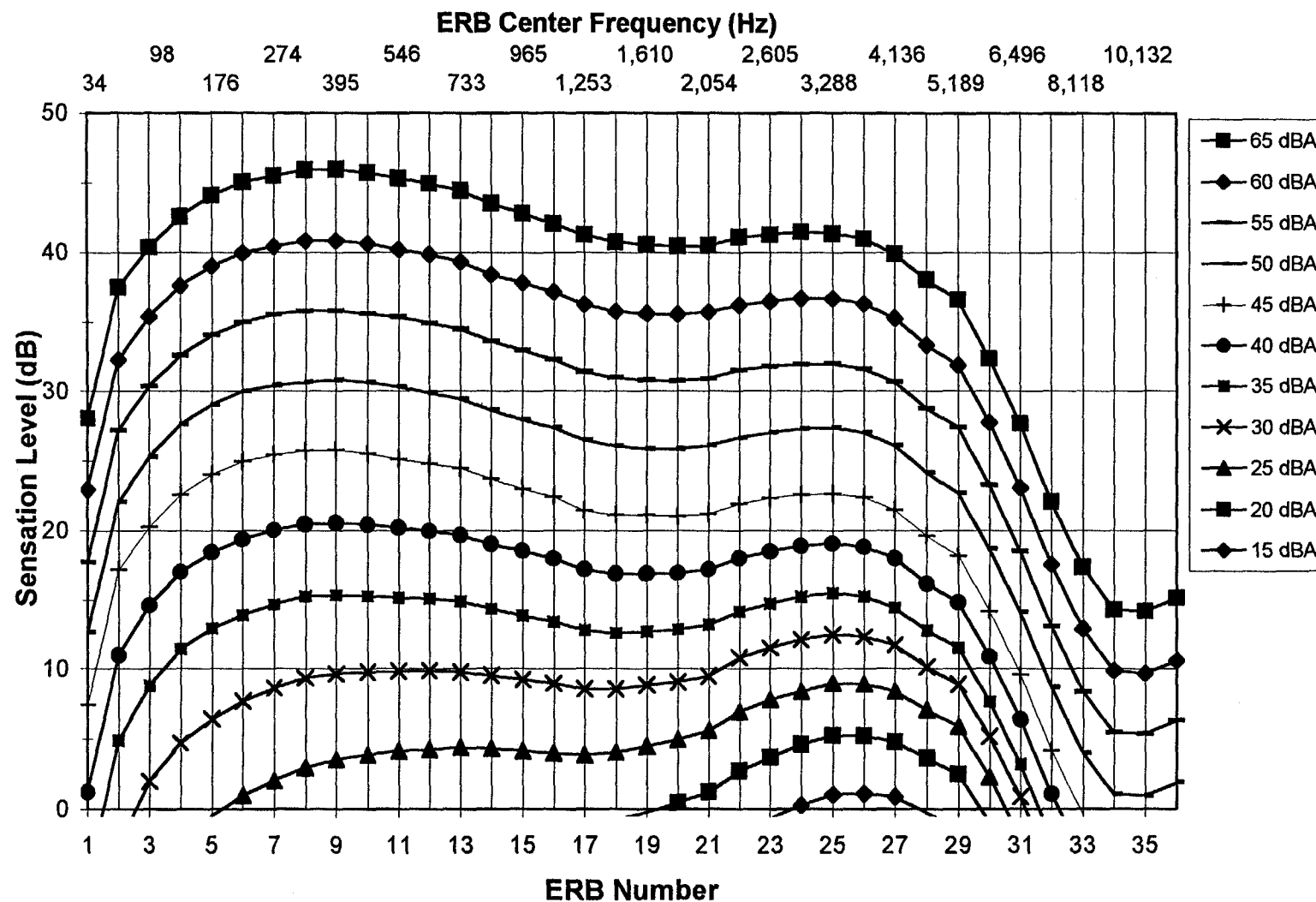
CONCLUDING REMARKS

This effort completes, along with a companion paper,[23] the initial development of a set of general environmental audible-noise impact-assessment computer programs, since 1996, planned to be consolidated into a summary program, *ENSOUND*. In alphabetical order, the subprograms are titled *ENAUDIBL* (relative audibility of sounds), *ENMASK* (residual environmental masking-noise spectra), *EXAIR* (air absorption), *EXBAR* (finite-length barriers), *GROUNDFX* (ground-cover absorption effects), and *SPECTRAN* (spectrum transformations).[15-23] Future efforts will focus on compilation of typical sound-power (L_w in dB//1 pW) spectral data for construction (diesel-engine powered) equipment or power-generation facilities correlated with parameters such as horsepower, kilowatts, and rotational speed.

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