

# Estimation of Environmental Noise Impacts within Architectural Spaces

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## ABSTRACT

Public Law 91-596, "Occupational Safety and Health Act of 1970," Dec. 29, 1970, stimulated interest in modeling the impacts of interior noise on employees, as well as the intelligibility of interior public-address and other speech intra-communication systems. The classical literature on this topic has primarily featured a statistical uniform diffuse-field model. This was pioneered by Leo L. Beranek in the 1950s, based on energy-density formulations at the former Bell Telephone (AT&T) Laboratories in the years from 1930 to 1950. This paper compares the classical prediction approach to the most recent statistical methods. Such models were developed in the late 1970s and included innovations such as consideration of irregularly shaped (e.g., L-shaped) interior room spaces and coupled spaces.

## INTRODUCTION

Consideration of acoustical impacts on listeners within the interior of a structure requires attention to the different purposes of the room space (e.g., music performance or speech communication by the occupants) and the desirable acoustical effects wanted by the occupants. The scope of this paper is limited to consideration of general approximations of physical sound magnitudes. The many possible subjective reactions of listeners to culturally related sounds, such as musical and theatrical (entertainment) performances, are beyond the scope of this paper. (The reader is referred for such breath of coverage to Part IX, "Architectural Acoustics," of the *Encyclopedia of Acoustics*.<sup>1</sup>)

Prediction of room-space sound levels may be needed to analyze hearing-damage risk, interference with speech intelligibility, or psychological impacts (individual annoyance). The modeling challenge requires sequential consideration of significant sources of ambient sound and their locations, as well as the locations of the listeners within the room space of interest. Also, the acoustic characteristics of the room space that affect transmission from sources to listeners must be taken into account, such as room-space shape and distribution of bounding surfaces (including reflection/absorption coefficients). These are a relatively complex set of factors that are best modeled for engineering/design studies by statistical functions. Factors such as the Schroeder frequency ( $f_s$ ), early decay time (EDT), and room constant (R) are evaluated, among other standardized measures of room-space acoustic characteristics. These are discussed in sections that follow. Topics will be reviewed in the following sequence:

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1. Source sound spectra (amplitude and frequency distribution),
2. Room sound-pressure level spectra,
3. Hearing-damage risk criteria,
4. Speech intelligibility criteria, and
5. Individual-annoyance potential.

In 1954, Beranek proposed the classical uniform diffuse-field model for computing the sound-pressure level throughout a room.<sup>2</sup> Many models for architectural interior room spaces have been published during the years since then to account for more complex sets of conditions. These developments generally fall into two categories: 1) methodologies using highly flexible ray-tracing computations (“geometric models”) and 2) statistical predictions of acoustic energy-density distributions (for use when relatively restricted, highly idealized room-space conditions can be assumed). The ray-tracing models can have very theoretical and physically rigorous formulations, as are required for any room shapes including curved boundaries and complex source distributions. Such cases require the use of very fast, advanced mainframe computing power. However, many applications may be limited to strictly rectangular spaces, not including elongated (tunnel-like) or L-shaped spaces; these may be adequately modeled with easily programmed algebraic functions using readily available personal computers. This review is intended to identify and distinguish between various architectural space configurations, acoustic source distributions, and listening conditions that may be of interest.

For brevity, the term “room space” is hereafter abbreviated “RS.” Also, it is useful, for the purpose of a relatively brief review, to define a quantity termed “the Schroeder frequency,”  $f_s$ , which is defined as:

$$f_s = 2000 / T V$$

where:  $T$  = reverberation time (sec)  
 $V$  = volume of the RS ( $m^3$ )

Below this frequency, bounding surfaces of the RS are large relative to the wavelength of sound and “standing waves” may predominate in the total sound field. However, this is not likely to be the case except in relatively small rooms with highly reflective surfaces. In that case, the resulting sound field will vary strongly with position in the RS. For most situations, the condition can be avoided by use of diffusing (diffracting) bounding-surface features, as well as resonant low-frequency sound-absorption devices, to make the reverberant-sound amplitude more uniform throughout the RS. In most environmental-impact situations of practical concern, low-frequency standing waves will not be a problem because these frequencies are either not present from ambient sources or can be easily suppressed with acoustical treatments.

*Consequently, for the purpose of this paper, all further discussions are confined to analyses at frequencies above the Schroeder frequency.*

## **SOURCE SOUND SPECTRA**

Sources of acoustic energy (sound and structural vibration—emitted sound from surfaces) can originate from locations both external to and within the architectural RS of concern. Therefore, in the most general case, estimates (or measures) must be made of both kinds of sources, their

locations (either localized or distributed), and the resulting sound fields within the subject RS. This is necessary to be able to analyze the masking effect (if any) of ambient sounds and the resulting audibility of intrusive sounds (noise) in the RS. All of this is a preliminary step in assessing impacts such as hearing-damage risk, speech intelligibility, and individual annoyance. The number and spectral characteristics of these sources will determine which models are to be used for assessment of environmental noise impacts within the RS. Thus, the analytical methodology for a given case may vary greatly in the number and extent of computer programs to be used and the corresponding extent of required input data. The following paragraphs review some of the methods that are available and their recommended applications.

The total sound field within a room is the sum of acoustic power spectra radiated by sources within the RS and any significantly powerful emissions from the room boundaries (walls, floor, and ceiling). The latter can arrive by a variety of paths. These paths include the building structure as a whole, as well as the RS enclosing wall, ceiling, and floor elements. Wall elements commonly include radiation from heating, ventilation, and air-conditioning (HVAC) duct openings, as well as sound emitted from doors and windows, both from their surfaces and associated air-leakage paths. Each path attenuates the intensity of transmitted acoustic power by both the cross-sectional area ( $A$ ) and transmission loss (TL) of the path, in decibels (dB). The TL is also known internationally as the Sound Reduction Index ( $R$ ), which the term is used in the balance of this paper. This quantity is a function of wavelength (frequency,  $f$ ) and must be estimated (or measured) at 1/3 octave-band frequency intervals because of the rapid changes (slopes) in  $R$  as a function of  $f$ . Computation of all RS sound source energy paths that may exist can be extremely tedious. For such computations, the reader is referred to Chapter 93 in Ref. 1. By one means or another, a 1/3 octave-band spectrum and power-level source description must be provided for each acoustic energy source that makes a significant contribution to the RS interior sound field. This is essential to calculation of any masking of wanted sound by unwanted sound (noise) that exists within the RS at a specific listener-impact location. Examples of these impacts are: reduction of speech intelligibility and increased listener annoyance due to reduced audibility of the sound of interest.

Spectra (sound-pressure amplitude in dB vs. frequency) can be estimated using data for many typical environmental, HVAC, and industrial sources, as quantitatively defined by octave-band in Chapter 98 in Ref. 1. Conversion to 1/3 octave-band form can be accomplished with the computer program *SPECTRAN* by this paper's authors, as described in A&WMA papers 96-RA104.01<sup>3</sup> and 97-TA29.01.<sup>4</sup> Additional acoustic power spectra for environmental sources (e.g., transportation activities external to the building containing the subject RS) can be found elsewhere.<sup>5</sup>

Appropriate  $R$  spectra (Sound Reduction Index vs. frequency,  $f$ ) for structural (e.g., wall and window  $R$ s) must be subtracted from the selected RS external acoustic power spectra to estimate internal RS acoustic power source spectra. This requires both experience and careful architectural analysis using the techniques outlined in Chapter 93 in Ref. 1. These computational steps include assignment of each externally originated source to specific internal RS locations, i.e., wall surfaces, windows, doors, floors, ceiling, and HVAC duct terminations. However, in many situations, sources external to the RS are not very significant and may be neglected,

simplifying the impact analysis. The balance of this paper concerns analyses with all sources having assigned locations within the RS.

An alternative to computing total ambient room noise including external sources is the use of Beranek’s Balanced Noise (NCB) spectra. These are a set of amplitude vs. octave-band sound-pressure level functions that represent intrusive sound spectra at various levels typical of interior environments. The original, now-standardized set is illustrated in Figure 10 in Chapter 80 of Ref. 1, and is described in detail in Ref. 6. Figure 13 of Chapter 80 in Ref. 1 illustrates median ( $L_{50}$ ) levels in interior RS locations which are typified by the various levels of NCB spectra. The RS interior NCB level will approximate the  $L_{50}$  value given in Figure 13 of that reference for those applicable RS interior environments. We have converted the NCB octave-band spectra<sup>6</sup> in Table 1 to 1/3 octave-band levels in Table 2 and plotted them in Figure 1 for the convenience of the reader when estimating masking and audibility impacts, as outlined in the following section. These NCB spectra were converted to their equivalent 1/3 octave-band form using the *SPECTRAN* program, as described in Ref. 3. The 1/3 octave-band frequency resolution (instead of octave-band data) is required for accurate calculation of audibility, speech intelligibility, and individual annoyance impacts, as described later.

**Table 1.** Balanced Noise Criterion (NCB) Octave-Band Spectra<sup>6</sup>

O.-B. Cent. Freq. (Hz)	Balanced Noise Criteria												Threshold of Hearing
	65	60	55	50	45	40	35	30	25	20	15	10	
16	97.0	94.0	92.0	89.0	87.0	85.0	84.0	82.0	81.0	80.0	79.0	78.0	77.0
31.5	88.0	85.0	82.0	79.0	76.0	73.5	71.5	68.5	66.5	63.0	61.0	59.0	57.0
63	79.0	76.0	72.0	69.0	65.0	62.0	59.0	55.0	52.0	49.0	46.0	43.0	37.0
125	74.5	71.0	67.0	62.0	58.0	54.0	50.0	46.0	42.0	38.0	34.0	30.0	22.0
250	71.3	67.0	63.0	58.0	53.0	49.0	44.0	40.0	35.0	30.0	26.0	21.0	13.0
500	68.6	64.2	60.0	54.8	49.8	45.0	40.0	35.0	30.0	25.0	20.0	15.0	8.0
1000	66.0	61.4	57.0	51.6	46.6	41.8	36.8	31.8	26.8	21.8	16.8	11.8	5.0
2000	63.3	58.6	54.0	48.4	43.4	38.5	33.5	28.5	23.5	18.5	13.5	8.5	3.0
4000	60.7	55.8	51.0	45.2	40.2	35.3	30.3	25.3	20.3	15.3	10.3	5.3	
8000	58.0	53.0	48.0	42.0	37.0	32.0	27.0	22.0	17.0	12.0	7.0	2.0	

## COMPUTATION OF ROOM SOUND-PRESSURE LEVELS FOR REGULAR AND IRREGULAR RS SHAPES

We initially consider the majority of situations in which noise-impact analysis can be made for rectangularly bounded RSs with all acoustic power sources having specific distributed (surface) or concentrated (point) locations defined by orthogonal numerical coordinates. Practical models for predicting sound-pressure levels within these constraints have been developed during a four-year research program at the Virginia Polytechnic Institute and State University (VPI), Blacksburg, Virginia, during 1974 through 1975, under the direction of Professors L.D. Mitchell, C.J. Hurst, N.E. Eiss, and H.H. Robertshaw.<sup>7,8</sup> A companion research program was also conducted during 1973 and 1976 to develop more general ray-tracing (“geometric”) models for analysis of RSs of any (arbitrary) shape.<sup>9-11</sup> These models were originally provided to the National Aeronautics and Space Administration (NASA), but when transmitted electronically (along with other programs) they were lost due to a technical fault in transmission facilities. The five research reports (graduate thesis documents)<sup>7-11</sup> documenting developments of these models

have never been submitted for refereed publication, but their authors have certified their qualification via empirical testing during model development. The balance of the paper documents the two statistical-model studies.<sup>7,8</sup>

**Table 2.** Balanced Noise Criterion (NCB) One-Third Octave-Band Spectra

1/3 O.-B. Cent. Freq. (Hz)	Balanced Noise Criteria												Threshold of Hearing
	65	60	55	50	45	40	35	30	25	20	15	10	
12.5	94.6	91.6	89.7	86.7	84.9	83.0	82.2	80.3	79.4	78.7	77.8	76.9	76.0
16	91.6	88.6	86.4	83.4	81.3	79.2	78.0	75.8	74.6	73.0	71.8	70.6	69.3
20	88.6	85.6	83.1	80.1	77.6	75.3	73.8	71.3	69.8	67.3	65.8	64.2	62.7
25	85.6	82.6	79.8	76.7	73.9	71.5	69.7	66.8	64.9	61.6	59.8	57.9	56.0
31.5	82.6	79.6	76.4	73.4	70.3	67.7	65.5	62.3	60.1	56.0	53.7	51.5	49.3
40	79.5	76.5	73.0	70.0	66.5	63.8	61.3	57.7	55.2	51.6	49.0	46.5	42.6
50	76.3	73.4	69.5	66.6	62.7	59.9	57.0	53.1	50.3	47.2	44.3	41.4	35.9
63	73.2	70.2	66.0	63.2	59.0	56.0	52.8	48.6	45.4	42.8	39.6	36.4	29.2
80	72.0	68.9	64.7	61.0	56.9	53.5	50.0	45.9	42.4	39.2	35.7	32.2	24.7
100	70.8	67.5	63.4	58.8	54.9	51.1	47.3	43.2	39.4	35.7	31.8	28.0	20.1
125	69.6	66.1	62.1	56.7	52.8	48.6	44.5	40.6	36.5	32.2	28.0	23.8	15.6
160	68.5	64.7	60.7	55.5	51.2	47.1	42.6	38.7	34.2	29.7	25.5	21.1	12.9
200	67.5	63.3	59.4	54.3	49.5	45.5	40.7	36.8	32.0	27.1	23.1	18.3	10.2
250	66.4	62.0	58.0	53.1	47.9	44.0	38.8	34.9	29.7	24.6	20.7	15.5	7.5
315	65.5	61.1	57.0	52.0	46.9	42.7	37.6	33.2	28.1	23.0	18.7	13.6	6.0
400	64.6	60.2	56.1	51.0	45.9	41.4	36.3	31.5	26.5	21.5	16.7	11.7	4.4
500	63.8	59.4	55.2	50.0	45.0	40.0	35.1	29.8	24.9	19.9	14.7	9.7	2.9
630	62.9	58.4	54.2	48.9	43.9	39.0	34.0	28.9	23.9	18.9	13.8	8.8	2.0
800	62.0	57.5	53.2	47.8	42.8	38.0	33.0	27.9	23.0	18.0	12.9	7.9	1.0
1000	61.2	56.6	52.2	46.7	41.7	37.0	32.0	27.0	22.0	17.0	12.0	7.0	0.1
1250	60.3	55.6	51.2	45.7	40.7	35.9	30.9	25.9	20.9	15.9	10.9	5.9	
1600	59.4	54.7	50.2	44.6	39.6	34.7	29.7	24.7	19.7	14.7	9.8	4.8	
2000	58.5	53.8	49.2	43.5	38.5	33.6	28.6	23.6	18.6	13.6	8.6	3.6	
2500	57.6	52.8	48.2	42.5	37.5	32.6	27.6	22.6	17.6	12.6	7.6	2.6	
3150	56.7	51.9	47.2	41.4	36.4	31.5	26.5	21.5	16.5	11.5	6.5	1.5	
4000	55.9	51.0	46.2	40.3	35.3	30.5	25.5	20.5	15.5	10.5	5.5	0.5	
5000	55.0	50.0	45.2	39.3	34.3	29.3	24.3	19.3	14.3	9.3	4.3		
6300	54.1	49.1	44.2	38.2	33.2	28.2	23.2	18.2	13.2	8.2	3.2		
8000	53.2	48.2	43.2	37.1	32.1	27.1	22.1	17.1	12.1	7.1	2.1		
10000	52.3	47.2	42.2	36.1	31.1	26.0	21.0	16.0	11.0	6.0	1.0		

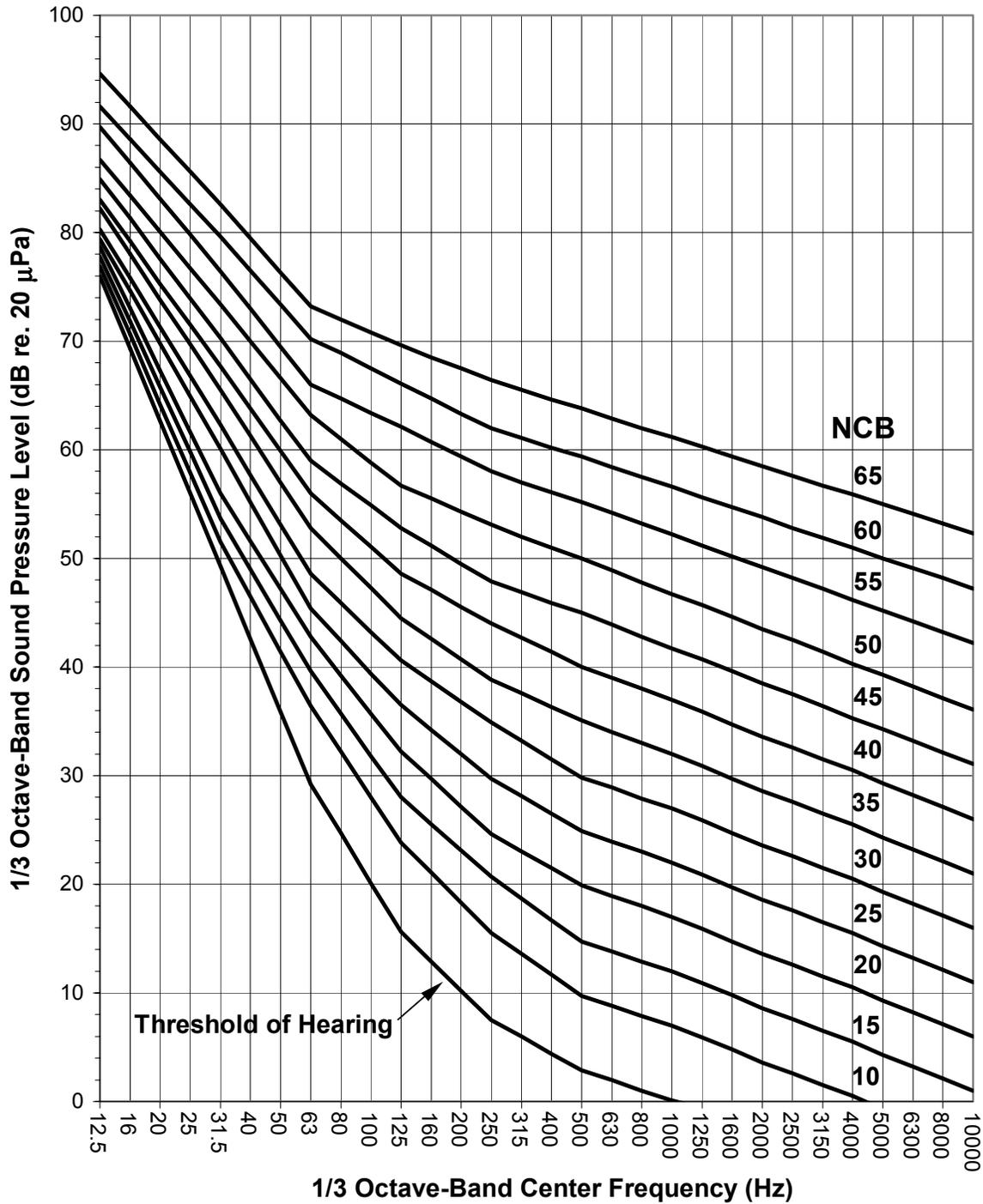
The two models are computations of sound levels within:

- A. Regularly shaped room spaces, and
- B. Irregularly shaped room spaces.

“Regularly shaped” rooms are defined as quadrilateral parallelepipeds (referred herein as “rectilinear”), i.e., the three orthogonal RS dimensions are such that the shortest dimension is greater than one-half the longest dimension. This is demonstrated by the statistical investigations of Allred and Newhouse,<sup>12</sup> which show that if this criterion is *not* met, the “mean free path” ( $L_{FP}$ ) will approach the *shortest* dimension of the room, in the limiting case of a very elongated

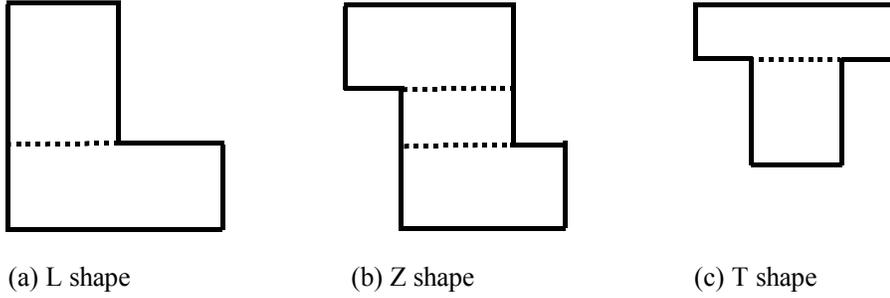
(tunnel or duct) or flattened (large room but relatively low ceiling) RS shape. These extremely “elongated” or “flattened” RS shapes must be analyzed with models especially developed for them. We plan to review such special cases in a future paper. If the RS shape consists of two or more rectilinear spaces coupled together, as shown in Figure 2, then it is designated “irregular.”

Figure 1: Balanced Noise Criteria (NCB) One-Third Octave-Band Spectra



If the RS shape departs from two or more joined quadrilateral parallelepipeds joined, e.g., is bounded by curved surfaces, it is designated “arbitrary.” Discussion of empirically developed, qualified mathematical sound-pressure level models for each of the two common categories of RS shapes is presented in the following sections.

Figure 2: Irregularly Shaped Room Spaces



### Models for Regularly Shaped RSs

The engineering/design model for sound-pressure level ( $L_p$ ) computation in the case of “regularly shaped” RSs is as follows:<sup>7</sup>

$$L_p = L_w + 10 \log \left\{ \left( \frac{Q_\psi e^{-\beta r}}{4\pi r^2} \right) + \left( \frac{\overline{L_{FP}}}{r} \right) \left[ \frac{4}{S(\alpha + \overline{L_{FP}}\beta)} \right] \right\} + C_r \quad (1)$$

where:

$L_p \equiv$  predicted sound-pressure level produced within the RS at a specified location (in dB ref. 20  $\mu$ Pa) at a specified frequency,  $f$ , or band-center frequency,  $f_c$ .

$L_w \equiv$  acoustic power level of a specified source radiated into the RS from a specified location (or surface) at a specified frequency,  $f$ , or band-center frequency,  $f_c$  (in dB ref. 1 pW).

$Q_\psi \equiv$  directivity factor for the specified source in the direction of a vector from the source to the specified location of the  $L_p$  prediction (“receiver location”). This value is the product of both any directivity inherent in the source in that direction ( $Q_S$ ) and directivity due to the source’s proximity to a reflecting surface ( $Q_R$ ), i.e.,  $Q_\psi = Q_S \cdot Q_R$ , e.g., the ground plane, nearby wall, etc. (dimensionless). Suggested  $Q_R$  values are presented in the next section.

$\beta \equiv$  air energy attenuation (“absorption”) rate (with distance), expressed as an exponent (“constant”) of the natural logarithm base “ $e$ ” (in  $m^{-1}$  units). (Words within quotes are commonly used alternate terms, but are *not* recommended for use, to avoid confusion with surface-absorption coefficients ( $\alpha$ ) that are used to define *reflected* acoustic energy from *surfaces*). See Ref. 13, Chapter 92 in Ref. 1, and Ref. 14 for detailed discussions.

$r \equiv$  straight-line separation of a specified “receiving” ( $L_p$ ) location from the specified source location (i.e., “range” of energy separation from a specified source to a specified “receiver”), in m.

$\overline{L_{FP}} \equiv$  mean free path of reflected sound rays within the RS (in m),  $\overline{L_{FP}} = 4V/S$

$V \equiv$  volume of the RS (in  $\text{m}^3$ )

$S \equiv$  total area of internal surfaces bounding the RS (in  $\text{m}^2$ )

$\bar{\alpha} \equiv$  total average absorption coefficient for the multiple surfaces bounding the RS (dimensionless).

$C_r \equiv$  characteristic resistance of air correction term, in dB ref. 400 mks rays in metric units  
 $= 10 \log [(293.15/T)^{0.5} (B/101.325 \text{ kPa})]$  in dB

$T \equiv$  prevailing temperature in  $^\circ\text{C} + 273.15$  in  $^\circ\text{K}$

$B \equiv$  barometric pressure in kPa.

Comments regarding the means of calculating (or estimating) values for each of the elements in the above equation are provided below.

The final term of Eq. (1), expressing a product of a temperature ratio and a barometric pressure ratio, is an air characteristic-resistance correction term, sometimes represented as a whole by the symbol “ $C_r$ ,” where  $C_r = 10 \log [(\rho c/400)]$ , in dB, where  $\rho$  is density of air in  $\text{kg}/\text{m}^3$  and  $c$  is speed of sound in  $\text{m}/\text{s}$ .<sup>14</sup> This is used for precise computation of  $L_p$ , correctly defined as:  $L_p = L_I + C_r$ , where  $L_I \equiv$  acoustic intensity,  $\text{Watts}/\text{m}^2$ , expressed in dB. However, at standard room temperatures and barometric pressures, the value of  $C_r$  is usually only a fraction of a decibel (dB) and, therefore, this correction is commonly neglected in engineering practice.

### ***Effective Total Directivity Factor ( $Q_\psi$ )***

The essential concept of the total directivity factor,  $Q_\psi$ , is the ratio of the wavefront area (spherical radius equal to “ $r$ ”) to the actual wavefront area through which the sound energy radiates, e.g., *if the wavefront shape were a sphere*:

$$Q_\psi = \frac{4 \pi r^2}{\text{actual area of radiation}}$$

In real situations, the source radiation wavefront rarely approximates a sphere. For example, simple cases are commonly given in tutorial texts when assuming sound radiation from an isotropic (non-directional) source:

$Q_\psi = 1$  for a source in free space (no reflecting surface “near”)

$Q_\psi = 2$  for a source at (“near”) a perfectly reflecting plane (floor/ground/wall) surface, i.e., hemispherical radiation (“half space”)

$Q_\psi = 4$  for source in (“near”) a 2-plane corner, i.e., intersection of two “infinite” planes (“quarter space”)

$Q_\psi = 8$  for a source in (“near”) an intersection of three perfectly reflecting “infinite” planes (“1/8 space”)

More realistically, if the non-directional source is midway between two parallel floor-ceiling planes (or walls) much closer to the source than other surfaces, the radiation wavefront shape would approach a cylindrical surface, for which:

$$Q_w = \frac{4 \pi r^2}{d (2 \pi r)} \quad \text{where } d = \text{separation of the two parallel planes.}$$

The term “near” is typically assumed to be approximated by one meter. Accordingly, if the source is at the end of a very elongated RS, e.g., a hallway, the wavefront approximates a plane with area slightly greater than the RS cross-sectional area:

$$Q_w \approx \frac{4 \pi r^2}{(HW)(HH)}$$

where  $(HW) \equiv$  hallway width and  $(HH) \equiv$  hallway height.

### ***Atmospheric Absorption (dB/m)***

The energy-attenuation-rate exponent,  $\beta$ , expressed as  $e^{-\beta r}$  in Eq. (1), in dB/1,000 m units, has been calculated for various combinations of relative humidity (in %) vs. temperature (in °C), using a methodology of Sutherland.<sup>13</sup> These computed values are listed in Table 2 of Chapter 92 in Ref. 1.

### ***Mean Free Path ( $\overline{L_{FP}}$ )***

The mean free path ( $\overline{L_{FP}}$ ) can be shown (by Monte Carlo statistical computations)<sup>12</sup> to be approximated as:

$$\overline{L_{FP}} = K_{FP} (xyz)^{1/3} \quad \text{where } K_{FP} \approx 1.5 \text{ and } x, y, \text{ and } z \text{ are the primary RS dimensions.}$$

This formulation for  $\overline{L_{FP}}$  proportional to the cube root of the product of the three primary dimensions of the RS provides  $\overline{L_{FP}}$  values within  $\pm 10\%$ , which affect calculated  $L_P$  levels only by fractions of a decibel, i.e., well within tolerances acceptable for environmental noise-impact assessments. However, if a more precise value of  $K_{FP}$  is desired, use the regression formula:

$$\overline{L_{FP}} = 0.7676 (xyz)^{1/3} - 0.585$$

### **Models for Irregularly Shaped RSs**

The previous section of this paper included Eq. (1) for use with “regularly shaped” RSs (formerly defined as simple “rectangular quadrilateral parallelepipeds,” i.e., basic single “shoebox” shapes). This section concerns a more complex case of RS shapes consisting of acoustically coupled combinations of 2 such RSs, as illustrated in Figure 2. The dashed lines represent virtual walls, i.e., open area dividing the component RSs. The referenced research at VPI for this case considered the effects of: 1) sound diffraction around corners in these RSs, and the coupling (flow) of acoustic energy from one RS to the other through (in both directions) the

common (coupled) area indicated by dashed lines in Figure 2. These were factors which were not included in the formulation (Eq. (1)) for “regular” rooms. These “modifications” of the Eq. (1) were based on previous work of Beranek,<sup>2</sup> Maekawa,<sup>15</sup> Moreland,<sup>16</sup> Rathe,<sup>17</sup> and Tatge<sup>18</sup> for diffraction effects, and Mankovsky<sup>19</sup> for acoustic-coupling effects. In addition, Thompson’s<sup>7</sup> incorporation of an air absorption-rate effect in the “direct” term of Eq. (1) suggested the following formulation (Eq. (2)) for calculating the  $L_p$ , provided that all the sound sources and all listening ( $L_p$ ) locations are located in the same room (e.g., sub-room 1):

$$L_p = L_w + 10 \log \left\{ \left( \frac{Q_s e^{-\beta r}}{4\pi r^2} \right) + \left( \frac{\bar{L}_{FP}}{d} \right) \left[ \frac{4K_1 K_2}{s(1 - K_1 K_2)} \right] \right\} + C_r \quad (2)$$

where:

$\Delta L$  (attenuation due to diffraction) is calculated using the following equations for the cases of right-angle wedge and screen, respectively:

Fresnel Number	Attenuation ( $\Delta L$ )	
	Right-Angle Wedge	Screen
$N < -0.3$	0 dB	0 dB
$-0.3 \leq N \leq -0.13$	0 dB	Equation (3b)
$-0.13 \leq N \leq -0.055$	Equation (3c)	Equation (3c) + 1.8 dB
$-0.055 < N < 0.0$	Equation (3d)	Equation (3d) + 1.8 dB
$0.0 \leq N \leq 0.105$	Equation (3e)	Equation (3e) + 1.8 dB
$0.105 < N \leq 1.0$	Equation (3f)	Equation (3f) + 1.8 dB
$N > 1.0$	Equation (3a) – 1.8 dB	Equation (3a)

(The term “right-angle wedge” in the above table refers to the case when the sound propagation from source location to  $L_p$  assessment location is diffracted primarily around a corner formed by surfaces at approximately 90° separation, but greater than about 45° separation. The term “screen” refers to the case when the aforementioned propagation is primarily diffracted around a very thin plane structure, i.e., thickness  $\ll$  1 wavelength, e.g., “screen,” “barrier wall,” etc., i.e.,  $\gg$  90° to nearly 360° angular separation.)

$$\Delta L = 13 \text{ dB} + 10 \log_{10} N \quad (3a)$$

$$\Delta L = 1.38275 + 3.066728N^1 + 1.369507N^2 + 0.2088855N^3 + 0.01086576N^4 \quad (3b)$$

$$\Delta L = 0.7707015 - 3.066728N - 133.3737N^2 \quad (3c)$$

$$\Delta L = 3.174147 + 111.4146N + 2622.701N^2 + 23.92958N^3 \quad (3d)$$

$$\Delta L = 3.362068 + 98.35458N - 1456.996N^2 - 13741.84N^3 + 5406024.4N^4 - 3246041N^5 \quad (3e)$$

$$\Delta L = 4.63456 + 13.78564N - 7.756586N^2 - 9.653335N^3 + 15.29918N^4 - 5.318671N^5 \quad (3f)$$

$N \equiv$  Fresnel number =  $2 \delta / \lambda$ , dimensionless

$\delta \equiv$  difference between the diffracted sound-source propagation path to the listener location and the direct-path (straight-line) separation between these two points (m)

$\lambda \equiv$  wavelength =  $c/f$  = speed of sound propagation,  $c$  (m/s), divided by frequency,  $f$  (Hz), in m.

$d \equiv$  source-receiver separation distance; must be greater than  $\overline{L_{FP}}$  (m)

$s \equiv$  area of opening between rooms (m<sup>2</sup>)

$K_1 \equiv$  coupling coefficient 1 =  $s / (\overline{\alpha}_1 S_1 + s)$

$K_2 \equiv$  coupling coefficient 2 =  $s / (\overline{\alpha}_2 S_2 + s)$

$S_1$  and  $S_2 \equiv$  surface areas bounding sub-rooms 1 and 2

$\overline{\alpha}_1$  and  $\overline{\alpha}_2 \equiv$  average absorption coefficients of surfaces bounding sub-rooms 1 and 2

$C_r \equiv$  characteristic resistance of air correction term (formula in the previous section)

When verification of the Eq. (3) algorithm was performed, using 2 different real industrial coupled-space venues, errors at all frequencies (in the range from the Schroeder frequency to 8,000 Hz) did not exceed 1 dB. However, errors in predicted  $L_p$  at locations in sub-room 2 (in the “shadow zone” for diffracted propagation) were as high as 4 dB. Another algorithm was devised (Eq. (4)), which yielded only 1 dB maximum errors in the shadow zone:

$$L_p = L_w + 10 \log \left\{ \left( \frac{Q_\psi e^{-\beta r} 10^{-\Delta L/10}}{4 \pi r^2} \right) + \left( \frac{\overline{L_{FP}}}{d} \right) \left[ \frac{4}{S_1 \overline{\alpha}_1 + S_2 \overline{\alpha}_2} \right] \right\} + C_r \quad (4)$$

Zinskie<sup>8</sup> states: “A further experimental study of the relationship between room (sound) absorption and reverberant field tapers (rate of  $L_p$  reduction with separation from source) might provide the basis for a new, and better, (statistical) room acoustic theory.” (Words in parentheses are the authors’ edits). He also cites Thompson’s<sup>7</sup> method for computation of source directivity ( $Q_\psi$ ) as important to minimize errors in the  $L_p$  computation.

## ENVIRONMENTAL NOISE-IMPACTS ASSESSMENTS

Methodologies for estimation of three forms of fundamental noise impacts (not dependent on cultural or sociological factors) are outlined below: 1) assessment of hearing-damage risk, 2) computation of speech intelligibility, and 3) estimation of individual-annoyance potential. All three recommended methodologies require, first, determination of an interior RS sound-pressure level *spectrum* evaluated by 1/3 octave-bands of frequency or by equivalent rectangular bandwidth (ERB) of frequency, as defined in Ref. 3, 4, and 20.

### Assessment of Hearing-Damage Risk

Hearing damage is commonly defined in terms of “temporary threshold shift” (TTS) and “permanent threshold shift” (PTS), depending basically on either a highest-level noise exposure for a brief time period, producing a temporary deafness, i.e., elevation of minimum perceived noise level (hearing threshold), or an essentially permanent degree of deafness produced by a noise exposure at relatively lower levels, but for 8 h every working day. Ward has documented the lowest noise levels producing PTS as about  $L_p = 80$  dB in any 1/3 octave-band or ERB frequency band containing frequencies between 3 kHz and 6 kHz when persons are exposed for

8 h every work day (Chapter 119 in Ref. 1). However, extremely short time exposures, of no more than 0.1 seconds to noise  $L_p$  at any frequency, exceeding about 120 dB, can produce temporary (TTS) deafness (Chapter 123 in Ref. 1).

## **Speech Intelligibility**

The primary model for computation of speech intelligibility, in percent, is contained in ANSI Standard S3.5-1997.<sup>21</sup> A closely related reference concerns the intelligibility of speech when using the telephone and as transmitted over loudspeaker systems.<sup>22</sup> Computation of specific degrees of speech intelligibility under the extremely varied conditions that can exist within an RS, as covered by this standard, are too complex to be usefully explained in a paper of this limited length. The fundamental requirements are, first, estimation of each RS masking noise source spectrum,  $L_p$ , by ERB or critical bandwidths and, second, estimation of the same type of  $L_p$  vs. subjective bandwidths for the speech sound wanted to be understood by the listener, as received at his/her specific location. The former includes such variables as room reverberation and distance within the RS of each masking noise source from the listener. The speech sound source variables include talker degree of voice effort and any distortion in an electroacoustic (“audio”) speech source, e.g., telephone or loudspeaker.

Accordingly, our comment herein is limited to the use of a Speech Interference Level (SIL) criterion.<sup>23</sup> Figure 6 in Chapter 80 of Ref. 1 provides a basis for estimating if speech intelligibility is good (> 97%) for a range in several of the masking noise and speech-source variables listed above. A future task is planned by the authors to develop a practical RS speech intelligibility computational methodology using the fundamental principles reviewed in Ref. 3, 4, 24, and Chapter 123 of Ref. 1.

## **Individual-Annoyance Potential**

The methodology for this computation is described in Ref. 25. Specifically, the portion of the paper titled “The Fidell Probabilistic Noise Audibility and Individual Annoyance Prediction (IAP) Model” provides detailed listing of the steps in the calculation methodology. This is a probabilistic (vs. deterministic) model for predicting the audibility level of sound (e.g., speech “signal”) in the presence of a background masking noise, e.g., RS total background noise (incl. reverberation spectrum). In turn, the computed audible spectrum is analyzed for the maximum audible 1/3 octave-band and a corresponding most-probable degree of annoyance (i.e., “none,” “slight,” “moderate,” “very annoyed,” or “extremely annoyed,” depending also on non-auditory factors such as the listener’s attitude toward the sources of any masking noise and the level of concentration by the listener on the speech sound of interest).

## **CONCLUSIONS**

The recovered unpublished architectural acoustics models developed during 1973 through 1976 at VPI along with later references included mainly in the Ref. 1, as well as the environmental noise-impact models documented in the A&WMA Acoustic Section papers prepared by the ANL staff since 1996, provide a basis for preparation of environmental RS noise-impact models for performing noise impact assessments. In particular, both statistical and geometric room acoustics models are planned for future development.

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**Key Words:** statistical room acoustics, geometric room acoustics, hearing-damage risk, speech intelligibility, individual-annoyance potential, noise.