Chapter 6

Sound and Noise

The general interest in this topic stems from the steadily growing incidence in today's modern industrial workplace, of sound and/or noise-induced hearing impairments (mostly partial, but occasionally, extending even to total hearing loss). The differences between sounds and noise are subjective. Sounds are considered to be something pleasant or useful — such as music [pleasant] or speech [useful]. Noise, in contrast, is thought of as being unpleasant, consisting of such things as the sounds of a table saw cutting wood or a fingernail scratching a chalkboard. This chapter will focus on the factors, parameters, and relationships that permit an accurate assessment of the potential for physiological damage caused by the ambient noise levels that exist in the workplace.

RELEVANT DEFINITIONS

Categories of Noise

Continuous Noise

An unbroken sound, made up of one or more different frequencies of either constant or varying sound intensity/sound pressure level, is referred to as **Continuous Noise**. If such a sound is constant and unvarying in its amplitude, it would be referred to as "steady" **Continuous Noise**. The alternative to this would be "varying" **Continuous Noise**. **Continuous Noise** is a fairly common occurring phenomenon – both in the industrial and the natural environment.

In the natural environment, one might regard the sound of a waterfall as "steady" **Continuous Noise**, while the sounds of wind blowing through a forest would be in the "varying" category.

In the industrial environment, the sound of a rotating electric motor (i.e., a fan, a pump, etc.) would be "steady" **Continuous Noise**, while the operation of a floor waxer, relative to a fixed observer, would be "varying" **Continuous Noise**.

Continuous Noise is an extremely useful concept. In assessing the potential hazards of any noise filled environment, one attempts to quantify the existing noise pattern in terms of the "steady" **Continuous Noise** that could, in theory, replace it without altering any of the adverse effects that might be being experienced by a human observer. For any environment, an $L_{equivalent}$, or the "steady" equivalent **Continuous Noise** level, as described above, can usually be determined; the actual sound intensity level of this "steady" **Continuous Noise** — which equals $L_{equivalent}$ — can then be used to evaluate the overall sound hazard that is posed to individuals who must occupy that environment.

Intermittent Noise

Intermittent Noise is a broken or non-continuous sound (i.e., sound bursts or periods of time during which there are intervals of quiet [non-sound] and subsequent intervals during which there is measurable sound). **Intermittent Noise** can also be made up of one or more different frequencies of sound, of either constant or varying intensity or sound level. The sound of an operating typewriter would be considered an intermittent noise.

Although such a category of noise is more difficult to relate to in the context of an $L_{equivalent}$, such a determination can be, and frequently is, made simply by integrating, over time, the entirety of the noise regime in any setting. Most commercially available sound level meters have the capability to provide an $L_{equivalent}$ for any situation in which sound is to be measured, whether this ambient sound or noise is intermittent, continuous, or a mixture of these different categories.

Characteristics of Sounds and/or Noise

Frequency

The **Frequency** of any sound or noise is the time rate at which complete cycles of high and low pressure regions [compressions and rerefactions] are produced by the noise or sound source. The most common unit of sound **Frequency** is the Hertz (abbreviated, Hz), which is the number of complete cycles that occur in a period of one second. The frequency range over which the human ear can hear varies with age and circumstance; however, a normal hearing "young" ear will usually be able to distinguish sounds, at moderate levels, in the range 20 to 20,000 Hz = 20 to 20,000 cycles/second.

Frequency Band

A sound can be made up of a single frequency — i.e., a tuning fork set at middle “C”; however, it is far more common for a sound or a noise, coming from any source, to be made up of a combination of different frequencies. Whenever a sound or a noise consists of a set of closely related frequencies, this set can be described as a **Frequency Band**. To identify any specific **Frequency Band**, one need only identify the range of frequencies that make it up, namely, by the lowest and the highest frequency in its “inventory”. These two frequencies are known as the “Upper & Lower Band-Edge Frequencies” of the particular **Frequency Band** being described.

Octave Bands & Bandwidths

Probably the most commonly used Frequency Band would be the **Octave Band**. A typical **Octave Band** is always characterized by the single frequency numerically located at its geometric center. The “Center Frequency” for any **Octave Band** is the *geometric mean* of its “Upper & Lower Band-Edge Frequencies”.

A second important characteristic of an **Octave Band** is the range of frequencies in it, or its **Bandwidth**. The **Bandwidth** of any Frequency Band is the range between its “Upper & Lower Band-Edge Frequencies”.

Typically, for a full **Octave Band**, this range will be up to one full octave in total **Bandwidth** — the principal characteristic of one full octave is that its highest frequency [the Upper Band-Edge Frequency] is always exactly twice its lowest frequency [the Lower Band-Edge Frequency]. A tabulation of the standard single, or full, **Octave Bands** is shown at the top of Page 6-3.

FULL OCTAVE BANDS

Center Frequency	Lower Band-Edge Frequency	Upper Band-Edge Frequency
31.3 Hz	22.1 Hz	44.2 Hz
62.5 Hz	44.2 Hz	88.4 Hz
125.0 Hz	88.4 Hz	176.8 Hz
250.0 Hz	176.8 Hz	353.6 Hz
500.0 Hz	353.6 Hz	707.1 Hz
1,000.0 Hz	707.1 Hz	1,414.2 Hz
2,000.0 Hz	1,414.2 Hz	2,828.4 Hz
4,000.0 Hz	2,828.4 Hz	5,656.9 Hz
8,000.0 Hz	5,656.9 Hz	11,313.7 Hz
16,000.0 Hz	11,313.7 Hz	22,627.4 Hz

Sound Wavelength

The **Wavelength** of a **Sound** is the precise distance required for one complete pressure cycle (i.e., one cycle of high [compressed] and low [rarefied] pressure regions) for that frequency of sound. Since sound is a periodic wave phenomenon — even though a markedly different one than the more classic example, light — it can be characterized in terms of its wavelength. This is most easily recognized by considering such things as organ pipes, the lengths of which will always relate to the wavelength of the sound that the particular pipe produces.

Pitch

The **Pitch** of a sound is the subjective auditory perception of the frequency of that sound. It, of course, depends upon the sound frequency, but also on its waveform, on the number of harmonics or overtones present, and on the overall sound pressure level.

Velocity of Sound

The **Velocity of Sound** is the speed at which the sequential regions of high and low pressure propagate away from the source of the sound. For all practical purposes this velocity can be considered to be a constant through whatever medium the sound is transiting. It varies directly as the square root of the density of the medium involved, and inversely as the compressibility of that medium. For example:

Medium	Velocity of Sound
air	~ 1,130 ft/sec
sea water	~ 4,680 ft/sec
hard wood	~ 13,040 ft/sec
steel	~ 16,550 ft/sec

Loudness

The **Loudness** of a sound is an observer's impression of its amplitude. This subjective judgment is influenced strongly by the characteristics of the ear that is doing the hearing.

Characteristic Parameters of Sound and Noise

Sound Intensity & Sound Intensity Level

The **Sound Intensity** of any sound source at any particular location is the average rate at which sound energy from that source is being transmitted through a unit area that is normal to the direction in which the sound is propagating. The most common units of measure for Sound Intensity are joules per square meter [m^2] per second, which are also equal to units of watts per square meter [m^2].

Sound Intensity is usually expressed in terms of an appropriate **Sound Intensity Level**. This parameter is determined by ratioing the Sound Intensity of some noise/sound against the accepted reference base Sound Intensity, which is 10^{-12} watts/m^2. When determined in this manner [see Equation **#6-3** on Page 6-9], the units of the Sound Intensity Level will be in decibels [dBs].

Sound Power & Sound Power Level

The **Sound Power** of any sound source is the total sound energy radiated by that source per unit time. The most common units of measure for Sound Power are watts.

Sound Power is usually expressed in terms of an appropriate **Sound Power Level**. This parameter can be calculated by ratioing the Sound Power of some noise/sound source against the accepted reference base Sound Power, which is 10^{-12} watts. When determined in this manner [see Equation **#6-4** on Page 6-9], the units of the Sound Power Level will also be in decibels [dBs].

Sound Pressure

Sound Pressure normally refers to the RMS values of the pressure changes, above and below atmospheric pressure, which are used to measure steady state or continuous noise. The most common units of measure for **Sound Pressure** are:

newtons per square meter = n/m^2 = pascals

[1 n/m^2 = 1 Pa]

dynes per square centimeter = d/cm^2

microbars

Root-Mean-Square [RMS] Sound Pressure

The **Root-Mean-Square [RMS]** value of any changing quantity, such as sound pressure, is equal to the square root of the mean of the squares of all the measured instantaneous values of that quantity.

Common Measurements of Sound Levels

Sound Pressure Level

Evaluation and/or measurement of any sound or noise, from the perspective of the characteristics of the healthy human ear, poses a difficult problem. This problem arises because of the very wide range of Sound Pressures that the human ear can hear without incurring damage. The healthy human ear can detect sounds at extremely low Sound Pressures [i.e., L_P =

20 μPa], and can survive without damage sounds having very high Sound Pressures [i.e., $L_P = 2 \times 10^8$ μPa = 200 Pa].

When evaluated at a reference frequency of 1,000 Hz, the "effective operating range" of a healthy human ear involves 7+ orders of magnitude of actual Sound Pressures. Because these "human hearing related" significant Sound Pressures vary over such an extremely wide range, the parameter that is most commonly used to describe Sound Pressures is the **Sound Pressure Level** [the **SPL**]. This parameter can be determined by ratioing the measured Sound Pressure of some noise or sound source against the reference base Sound Pressure of 2×10^{-5} n/m^2 = 2×10^{-5} Pa = 20 μPa. When determined in this manner [see Equation **#6-2** on Page 6-8], the units of the Sound Pressure Level will also be expressed in decibels [dBs]. The decibel was chosen in this situation simply because logarithmic units of measure are virtually always judged to be more useful when dealing with parameters whose values may vary over more than 4 or 5 orders of magnitude.

Threshold of Hearing

The **Threshold of Hearing** for a healthy human ear, expressed in decibels and determined at a frequency of 1,000 Hz, is **0 dB**. This is the approximate sound of a feather falling in an otherwise completely quiet room — it is doubtful that the frequency of sound produced by a falling feather would be 1,000 Hz; however, the author can find no other reference to any physical event that would produce this low level of an SPL.

Threshold of Pain

The **Threshold of Pain** for a healthy human ear, also expressed in decibels and also determined at a frequency of 1,000 Hz, is approximately **140** to **145 dB**. At this SPL, an exposed individual would likely experience both permanent damage to his or her hearing and in addition experience actual pain, thus the name. The sound of a commercial jet plane taking off, 25 feet from the unprotected observer, would produce this approximate SPL.

Sound and/or Noise Measurement Time Weightings

In the quantification of various Sound Pressure Levels [in decibels], there are four different commonly used averaging periods, or **Time Weightings**, that are part of the standard RMS detection method. These four are: Peak, Impulse, Fast, and Slow Noise Weightings.

Peak Noise

A burst of sound having a duration of less than 100 milliseconds is considered to be in the **Peak Noise** category. Such sounds will also fall under the category of Impulsive or Impact Noise.

Impulsive or Impact Noise

The types of noise produced by such things as a gun being fired, the operation of an industrial punch press, or the use of a hammer to drive a nail are all highly transient sound phenomena, and are usually treated as **Impulsive or Impact Noises**. This type of noise is defined to be any sound having an amplitude rise time of 35 milliseconds or less, and a fall time of 1,500 milliseconds or less.

Fast Time Weighted Noise

Sound pressure level measurements using a 125-millisecond moving average time weighting period are said to have been determined using **Fast Time Weighting**.

Slow Time Weighted Noise

Sound pressure level measurements using a 1.0-second moving average time weighting period are said to have been determined using **Slow Time Weighting**.

Sound and/or Noise Measurement Frequency Weightings

Linear Frequency Weighting

Any measurement of a sound pressure level can be thought of as the unique "sum" of the ten discrete sound pressure levels of the standard Octave Bands that have made up the sound being monitored. If these measurements are developed without the application of any internal "adjustments" by the sound level meter that is being used — i.e., the meter neither increases nor decreases its measured decibel level of any of the Octave Bands before developing its overall "sum" measurement — then the result is said to have been produced using **Linear Frequency Weighting**. Whenever one attempts to characterize a noise, for the purpose of designing or implementing some sort of sound mitigation, the measurements will probably employ a Linear Weighting approach. If it is desired to measure any one single Octave Band, **Linear Frequency Weighting** will always be employed.

A-Frequency Weighting Scale

The **A-Frequency Weighting Scale** [covered in complete quantitative detail in the next sub-section of this Chapter, namely, **RELEVANT FORMULAE & RELATIONSHIPS**, as the first part of Equation **#6-10**] is a set of measurement weightings that must be applied to the decibel reading for each of the standard Octave Bands that make up the sound being measured. The application of these weighted adjustments — by the internal A-Weighting network in the sound level meter that is making the measurement — ensures that the resultant indicated overall Sound Pressure Level measurement will be of a magnitude that constitutes the very best approximation to what a normal human ear would have perceived. The A-Weighting Scale is usually thought to apply to noises having relatively low level intensities. Sound Pressure Level measurements made using this weighting are always identified by the inclusion of the letter "A" after the "dB" unit; thus, **dBA**. The **A-Frequency Weighting Scale** is the most commonly used and widely accepted frequency weighting scale employed in sound pressure level measurements today.

B-Frequency Weighting Scale

The **B-Frequency Weighting Scale** [also covered in complete quantitative detail in the next sub-section of this Chapter, namely, **RELEVANT FORMULAE & RELATIONSHIPS**, as the second part of Equation **#6-10**] is one of the two alternative sets of measurement weightings that must also be applied to each of the standard Octave Bands that make up any sound. The application of these particular weightings — again by a sound level meter's internal B-Weighting network — is designed to produce a result that approximates what a normal human ear would have perceived to noises having relatively moderate, in contrast to low, intensities. Sound Pressure Level measurements made using this category of weighting are always identified by the inclusion of the letter "**B**" after the dB unit, thus, **dBB**. The **B-Frequency Weighting Scale** is not in very wide use today.

C-Frequency Weighting Scale

The **C-Frequency Weighting Scale** [also covered in complete quantitative detail in the next sub-section of this Chapter, namely, **RELEVANT FORMULAE & RELATIONSHIPS**, as the third and final part of Equation **#6-12**] is the second of the two alternative sets of measurement weightings that must also be applied to each of the standard Octave Bands that make up any sound. The application of these particular weightings — again by a sound level meter's internal C-Weighting network — is designed to produce a measurement that approximates what a normal human ear would have perceived as high intensity noises. Sound Pressure Level measurements made using this category of weighting are always identified by the inclusion of the letter "**C**" after the dB unit, thus, **dBC**. The **C-Frequency Weighting Scale** is only rarely used today.

RELEVANT FORMULAE & RELATIONSHIPS

Approximate Velocity of Sound in Air

The velocity of sound in the earth's atmosphere varies directly as the square root of the density of the air. The most easily measured parameter that affects the velocity of sound in the air is its prevailing ambient temperature.

Equation #6-1:

The following relationship, Equation **#6-1**, was empirically derived; however, it has proven to be very accurate for calculating the **Velocity of Sound in Air** over a very wide range of ambient temperatures.

$$\mathbf{V = 49\sqrt{t + 459}}$$

Where:

$\mathbf{V}$ = the Velocity of Sound in Air, measured in feet per second; &

$\mathbf{t}$ = the Ambient Air Temperature, measured in relative English Units, namely, °F.

Basic Sound Measurements — Definitions

Equation #6-2:

The following relationship, Equation **#6-2**, constitutes the definition of a **Sound Pressure Level**. The expression relates the measured Analog Sound Pressure Level to a "Base Reference Analog Sound Pressure Level", defining the common logarithm of this ratio to be the **Sound Pressure Level**. Because of the potential for extremely wide variations in the measurable analog Sound Pressures, the unit of measure for the **Sound Pressure Level** is the decibel, which, as stated above, is logarithmic and, as such, is better suited as a measure of numeric values, the magnitude of which can vary over several orders of magnitude.

$$\mathbf{L_P = 20\,\mathit{log}\left[\frac{P}{P_0}\right] = 20\,\mathit{log}\left[\frac{P}{2 \times 10^{-5}}\right] = 20\,\mathit{log}\,P + 93.98}$$

Where:

$\mathbf{L_P}$ = the **Sound Pressure Level**, measured in decibels (dBs);

$\mathbf{P}$ = the measured Analog Sound Pressure Level, in units of newtons/square meter (nt/m^2); &

$\mathbf{P_0}$ = the "Base Reference Analog Sound Pressure Level", which has been defined to have a value of 2×10^{-5} nt/m^2.

<u>Equation #6-3</u>:

This relationship, Equation **#6-3**, is the definition of a **Sound Intensity Level**. In this case, the equation relates the measured Analog Sound Intensity Level to a "Base Reference Analog Sound Intensity Level". As was true in the preceding case, this parameter also is measured in units of decibels, and again for the very same reasons.

$$\mathbf{L_I = 10\,\mathit{log}\left[\frac{I}{I_0}\right] = 10\,\mathit{log}\left[\frac{I}{10^{-12}}\right] = 10\,\mathit{log}\,I + 120}$$

Where:

$\mathbf{L_I}$ = the **Sound Intensity Level**, measured in decibels (dBs);

$\mathbf{I}$ = the Analog Sound Intensity Level, measured in watts/square meter (wts/m^2); &

$\mathbf{I_0}$ = the "Base Reference Analog Sound Intensity Level", which has been defined to have a value of 10^{-12} wts/m^2.

<u>Equation #6-4</u>:

This final analogous relationship, Equation **#6-4**, constitutes the definition of a **Sound Power Level**. As is the case for its two previous close relatives, this expression relates the measured Analog Sound Power Level to a "Base Reference Analog Sound Power Level". Like the two preceding equations, this one also provides **Sound Power Levels** in units of decibels, since the magnitudes of these values can also vary over a number of orders of magnitude.

$$\mathbf{L_{\mathit{P}} = 10\,\mathit{log}\left[\frac{\mathit{P}}{\mathit{P_0}}\right] = 10\,\mathit{log}\left[\frac{\mathit{P}}{10^{-12}}\right] = 10\,\mathit{log}\,\mathit{P} + 120}$$

Where:

$\mathbf{L_{\mathit{P}}}$ = the **Sound Power Level**, measured in decibels (dBs);

$\boldsymbol{P}$ = the measured Analog Sound Power Level, measured in units of watts (wts); &

$\boldsymbol{P_0}$ = the "Base Reference Analog Sound Power Level", which has been set to have a value of 10^{-12} wts.

Sound Pressure Levels of Noise Sources in a Free Field

Equation #6-5:

The following expression, Equation **#6-5**, identifies and relates the specific factors that must be accounted for when one determines the **Effective Sound Pressure Level** of any noise source in a "Free Field". For reference, a "Free Field" is any region (within which the noise source is located) that can be characterized as being free or void of any and all objects other than the noise source itself. Such a region permits the unhindered propagation of sound from the source in ALL directions. Because noise sources in the real world are seldom, if ever, in a true "Free Field", this expression has, as its final additive factor, a logarithmic term that effectively adjusts the resultant **Effective Sound Pressure Level** for any asymmetry that may exist in a real world "Non-Free Field" situation. Such factors effectively modify the "Free Fieldness" of the region where the noise source is located. As an example, a bell mounted on a wall would not be able to radiate sound in the direction of the wall; rather, it would effectively radiate sound only into a single spatial hemisphere. The factor that is used to achieve this result modification is called the Directionality Factor, and is defined below.

$$L_{P\text{-Effective}} = L_{P\text{-Source}} - 20\log r - 0.5 + 10\log Q$$

Where:

$L_{P\text{-Effective}}$ = the **Effective Sound Pressure Level**, evaluated at a point that is "r" feet distant from the noise source itself, measured in decibels (dBs);

$L_{P\text{-Source}}$ = the source Sound Pressure Level, also measured in decibels (dBs);

r = the distance from the point where the **Effective Sound Pressure Level** is to be measured, to the noise source, measured in feet (ft); &

Q = the Directionality Factor, a dimensionless parameter — as defined and valued below:

Q	=	**1**	for "spherical omnidirectional" radiating sources;
Q	=	**2**	for "single hemisphere" radiating sources;
Q	=	**4**	for "single quadrant" radiating sources;
Q	=	**8**	for "single octant" radiating sources

Addition of Sound Pressure Levels from Several Independent Sources

Equation #6-6:

The following expression, Equation **#6-6**, is one of the most frequently employed relationships in all of acoustical engineering. It provides the basic methodology for determining the cumulative effect of several noise sources (each producing noise at an identifiable Sound Pressure Level) on an observer. This relationship provides for the determination of the **Ef-**

fective Sound Pressure Level that would be experienced by an observer from the several noise sources.

For this determination, we assume the perspective of an observer whose relative location — among two or more noise sources — causes him or her to experience an overall noise exposure — i.e., an **Effective Sound Pressure Level** — that will be: (1) obviously greater than would have been for a situation involving only a single noise source, but (2) certainly not simply the sum of the several sound pressure levels. As a descriptive example, consider the starter at a drag race. Assume this person is standing midway between two mufflerless dragsters, each producing sound at 130 dBA. Clearly this person would be exposed to a sound pressure level greater than 130 dBA, but not simply the sum value of 260 dBA. **Equation #6-6** provides the solution to the addition of sound pressure levels from several different separate and independent sources.

$$\mathbf{L_{total}} = \mathbf{10}\,\boldsymbol{log}\left[\sum_{i=1}^{n} 10^{\left[L_i/10\right]}\right]$$

OR

$$\mathbf{L_{total}} = \mathbf{10}\,\boldsymbol{log}\left[10^{\left[L_1/10\right]} + 10^{\left[L_2/10\right]} + \ldots + 10^{\left[L_n/10\right]}\right]$$

Where: L_{total} = the total **Effective Sound Pressure Level** resulting from the "n" different noise sources, measured in decibels (dBs); &

L_i = the Sound Pressure Level of the **i**th of "n" different noise sources, also measured in decibels (dBs).

Calculations Involving Sound Pressure Level "Doses"

Equation #6-7:

The following expression, Equation **#6-7**, provides for the determination of the **Maximum Time Period** any worker may be safely exposed to some specifically quantified and/or **Equivalent Sound Pressure Level** from any number of noise sources.

$$T_{max} = \frac{8}{2^{\left[(L-90)/5\right]}}$$

Where: T_{max} = the **Maximum Time Period** — at any Equivalent Sound Pressure Level, L — to which a worker may be exposed during a normal 8-hour workday, measured in some convenient time unit, usually hours; &

L = the Sound Pressure Level (or Equivalent Sound Pressure Level) being evaluated for this situation, measured in decibels (dBs).

Equation #6-8:

The second relationship involving "doses" is Equation **#6-8**, which provides the basis for calculating the **Effective Daily Dose** that an individual would have experienced as a result of his or her having been exposed to several different well-quantified sound pressure levels, each of which occurred for some specific Time Period or Time Interval.

$$\mathbf{D} = \sum_{i=1}^{n} \frac{C_i}{T_{max_i}} = \frac{C_1}{T_{max_1}} + \frac{C_2}{T_{max_2}} + \ldots + \frac{C_n}{T_{max_n}}$$

Where: **D** = the **Effective Daily Dose** (of noise) to which an individual who has been exposed to a series of "n" different sound pressure levels, with each of these exposures lasting for a known Time Period or Time Interval, C_i; the **Effective Daily Dose**, **D**, is a dimensionless decimal number;

C_i = the overall ith Time Interval or Time Period during which the individual being considered was exposed to the ith sound pressure level; these time intervals will always have to be measured in some consistent unit of time, usually in hours; &

T_{max_i} = the **Maximum Time Period** that would be permitted for the ith specific sound pressure level to which an individual could be exposed; as defined by Equation **#6-7**, on Page 6-10.

> Note: For any value of **Effective Daily Dose**, **D** $\leq$ 1.00, the individual who has experienced this dose will have accumulated neither an excessive nor a harmful amount of noise. On the other hand, if this parameter assumes a value greater than 1.00, then the exposure would have to be classified as potentially harmful.

Equation #6-9:

The following expression, Equation **#6-9**, provides the relationship for determining the **Equivalent Sound Pressure Level** that corresponds to any identified **Daily Dose**.

$$L_{equivalent} = 90 + 16.61 \log D$$

Where: $L_{equivalent}$ = the **Equivalent Sound Pressure Level** that corresponds to any Daily Dose, with this parameter measured in decibels (dBs); &

D = the Daily Dose, as defined on the previous page, namely Page 6-11, by **Equation #6-8**.

Definitions of the Three Common Frequency Weighting Scales

Equation #6-10:

The following tabular listing serves as the defining descriptor for each of the three commonly used Frequency Weightings, as these weightings are applied to the measurement of any sound or noise. These weightings, which are applied to the specific Full or Unitary Octave Bands that make up the sound that is being monitored, are designed to provide a measured result that approximates the response of the human ear to sounds or noises of various intensities. Specifically, the **A-Weighting Scale** is thought to provide a result that approximates the response of the human ear to low intensity sounds or noises. The **B-Weighting Scale** provides a human ear based response to sounds or noises having a moderate or medium intensity. Finally, the **C-Weighting Scale** is thought to provide a similar result when applied to high intensity sounds or noises. The **A-Weighting Scale** is, by far, the most widely used of these three; the other two are now only rarely used.

All three Frequency Weighting Sales are in the form of "additions to" OR "deductions from" the Full or Unitary Octave Bands that make up the sound that is being monitored. Whenever the sound level meter being used to monitor some sound or noise has been set up to provide a result to which one of these Frequency Weightings has been applied, the resultant units of the measurement must have — as applicable — an "A", a "B", or a "C" appended to it — i.e., dBA for an **A-Weighting Scale** measurement, dBB for the **B-Weighting Scale**, and/or dBC for the **C-Weighting Scale**.

The following tabulation shows the additions OR deductions that must be applied to the various Octave Bands in order to make the required Frequency Weighting adjustments.

Full Octave Band, in Hertz	⟨Deductions⟩ OR Increments, in decibels A-Scale	B-Scale	C-Scale
31 Hz	⟨39⟩	⟨17⟩	⟨3⟩
63 Hz	⟨26⟩	⟨9⟩	⟨1⟩
125 Hz	⟨16⟩	⟨4⟩	0
250 Hz	⟨9⟩	⟨1⟩	0
500 Hz	⟨3⟩	0	0
1,000 Hz	0	0	0
2,000 Hz	1	0	0
4,000 Hz	1	⟨1⟩	⟨1⟩
8,000 Hz	⟨1⟩	⟨3⟩	⟨3⟩

Various Octave Band Relationships

Equation #s 6-11 & 6-12:

The following two relationships, namely, Equation **#s 6-11** & **6-12**, identify the specific relationships that apply to any Full or Unitary Octave Band, as specified by ANSI S1.11-1966 (R1975). Note, the nine Full or Unitary Octave Bands listed in the tabulation on the previous page, namely, Page 6-13 — as part of the Definitions of the three Frequency Weighting Scales — are the commonly accepted Full or Unitary Octave Bands. For the overall set of Full or Unitary Octave Bands, the Center Frequency of the "Middle" Octave Band is 1,000 Hz. Each member of this set of nine Full or Unitary Octave Bands will have the following characteristics:

(1) Each band will be one full octave in total Bandwidth — i.e., the Band's Lower Band-Edge Frequency will always be half of its Upper Band-Edge Frequency.

(2) The Center Frequency of each band will be the "Geometric Mean" of its Lower and its Upper Band-Edge Frequencies.

(3) Each band will have a Center Frequency that will be one half of the Center Frequency of the next higher Octave Band, and twice the Center Frequency of the next lower one.

The first two of these three overall relationships can be expressed quantitatively and are shown below.

Equation #6-11:

$$f_{upper-1/1} = 2\left(f_{lower-1/1}\right)$$

Equation #6-12:

$$f_{center-1/1} = \sqrt{\left(f_{upper-1/1}\right)\left(f_{lower-1/1}\right)} = \text{the "Geometric Mean"}$$

Where: $f_{upper-1/1}$ = the Upper Band-Edge Frequency for the specific Full or Unitary Octave Band being considered;

$f_{lower-1/1}$ = the Lower Band-Edge Frequency for the specific Full or Unitary Octave Band being considered; &

$f_{center-1/1}$ = the Center Frequency for the specific Full or Unitary Octave Band being considered.

Equation #s 6-13 & 6-14:

The following two relationships, Equation **#s 6-13** & **6-14**, as shown on Page 6-15, identify the specifics of a Standard Half Octave Band, also as specified by ANSI S1.11-1966 (R1975). For the overall set of Half Octave Bands, the Center Frequency of the "Middle" Octave Band is, like its Full or Unitary Octave Band counterpart, at 1,000 Hz. For the overall set of Half Octave Bands, the following set of characteristics always applies:

(1) Each Half Octave Band will be $1/\sqrt{2}$ Octaves in total Bandwidth, i.e., the Lower Band-Edge Frequency of each Half Octave Band will always be $1/\sqrt{2}$ of its Upper Band-Edge Frequency.

(2) The Center Frequency of each Half Octave Band will be the "Geometric Mean" of its Lower and its Upper Band-Edge Frequencies.

(3) Each Half Octave Band will have a Center Frequency that will be $1/\sqrt{2}$ of the Center Frequency of the next higher Half Octave Band, and $\sqrt{2}$ times the Center Frequency of the next lower one.

Again the first two of these three overall relationships can be expressed quantitatively and are shown below.

Equation #6-13:

$$\mathbf{f}_{\mathbf{upper-1/2}} = \left(\sqrt{\mathbf{2}}\right)\left(\mathbf{f}_{\mathbf{lower-1/2}}\right)$$

Equation #6-14:

$$f_{center-1/2} = \sqrt{\left(f_{upper-1/2}\right)\left(f_{lower-1/2}\right)} = \text{the "Geometric Mean"}$$

Where: $\mathbf{f}_{\mathbf{upper-1/2}}$ = the Upper Band-Edge Frequency for the specific Half Octave Band being considered;

$\mathbf{f}_{\mathbf{lower-1/2}}$ = the Lower Band-Edge Frequency for the specific Half Octave Band being considered; &

$\mathbf{f}_{\mathbf{center-1/2}}$ = the Center Frequency for the specific Half Octave Band being considered.

Equation #s 6-15 & 6-16:

The following two relationships, **Equation #s 6-15** & **6-16**, as shown on the following page, identify the specifics of a "$1/n^{th}$" Octave Band, also as specified by ANSI S1.11-1966 (R1975). For the overall set of $1/n^{th}$ Octave Bands, the Center Frequency of the "Middle" Band is, like its other counterparts, at 1,000 Hz. For the overall set of $1/n^{th}$ Octave Bands, the following set of characteristics always applies:

(1) Each $1/n^{th}$ Octave Band will be $1/\sqrt[n]{2}$ Octaves in total Bandwidth, i.e., the Lower Band-Edge Frequency of each $1/n^{th}$ Octave Band will always be $1/\sqrt[n]{2}$ of its Upper Band-Edge Frequency.

(2) The Center Frequency of each $1/n^{th}$ Octave Band will be the "Geometric Mean" of its Lower and its Upper Band-Edge Frequencies.

(3) Each $1/n^{th}$ Octave Band will have a Center Frequency that will be $1/\sqrt[n]{2}$ of the Center Frequency of the next higher Half Octave Band, and $\sqrt[n]{2}$ times the Center Frequency of the next lower one.

Again the first two of these three overall relationships can be expressed quantitatively and are shown on the following page.

Equation #6-15:

$$\mathbf{f_{upper-1/n} = \left(\sqrt[n]{2}\right)\left(f_{lower-1/n}\right)}$$

Equation #6-16:

$$f_{center-1/n} = \sqrt[n]{\left(f_{upper-1/n}\right)\left(f_{lower-1/n}\right)} = \text{the "Geometric Mean"}$$

Where:

$\mathbf{f_{upper-1/n}}$ = the Upper Band-Edge Frequency for the specific $1/n^{th}$ Octave Band being considered;

$\mathbf{f_{lower-1/n}}$ = the Lower Band-Edge Frequency for the specific $1/n^{th}$ Octave Band being considered; &

$\mathbf{f_{center-1/n}}$ = the Center Frequency for the specific $1/n^{th}$ Octave Band being considered.

SOUND & NOISE PROBLEM SET

Problem #6.1:

The average noontime, unshaded summer temperature in the Mojave Desert is 129°F. What will be the approximate speed of sound in the Mojave Desert under these conditions?

Applicable Definitions:	Velocity of Sound	Page 6-3
Applicable Formula:	Equation **#6-1**	Page 6-8
Solution to this Problem:	Page 6-31	

Problem Workspace

Problem #6.2:

On a calm day in January of any year, in Fairbanks, AK, the noontime temperature will typically be –35°C. What will be the speed of sound in air under such conditions?

Applicable Definitions:	Velocity of Sound	Page 6-3
Applicable Formulae:	Equation **#1-3**	Page 1-16
	Equation **#6-1**	Page 6-8
Solution to this Problem:	Page 6-31	

Problem Workspace

Problem #6.3:

The maximum continuous noise level that is permitted by OSHA is an SPL of 115 dBA (at this level, the maximum permitted duration of this sort of noise is limited to 7.5 minutes). What is the analog Sound Pressure, in Pascals, of noise at this SPL?

Applicable Definitions:	Sound Pressure	Page 6-4
Applicable Formula:	Equation **#6-2**	Page 6-8
Solution to this Problem:	Pages 6-31 & 6-32	

Problem Workspace

Problem #6.4:

The average analog Sound Intensity, measured at a distance of 2.0 meters, of a hummingbird hovering has been measured to be 2.45×10^{-7} watts/cm^2. What is the corresponding Sound Intensity Level, in dB, at this distance?

Applicable Definitions:	Sound Intensity & Intensity Level	Page 6-4
Applicable Formula:	Equation **#6-3**	Page 6-9
Solution to this Problem:	Page 6-32	

Problem Workspace

Problem #6.5:

The Sound Power Level of a top fuel dragster (at maximum engine and supercharger RPM) is 134 dB. To what analog Sound Power, expressed in watts, does this measured Sound Power Level correspond?

Applicable Definitions:	Sound Power & Power Level	Page 6-4
Applicable Formula:	Equation **#6-4**	Page 6-9
Solution to this Problem:	Page 6-32	

Problem Workspace

Problem #6.6:

At a distance of 300 feet, what sound pressure level, in dBA, would a ground observer, without hearing protection, experience if he were to witness and listen to the takeoff of a U.S. Navy F8U single jet fighter-interceptor? At takeoff, the sound pressure level of this aircraft's afterburner-assisted jet engine, which can be regarded as being directly on the ground, is 165 dBA.

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-5**	Page 6-10
Solution to this Problem:	Pages 6-32 & 6-33	

Problem Workspace

Workspace Continued on the Next Page

Continuation of Workspace for Problem **#6.6**

Problem #6.7:

At what altitude, measured in feet, would the fighter listed in Problem **#6.6** have to pass (measured to a point directly above the observer), in order for that observer to experience the identical sound pressure level that was calculated for the previous problem — in that case from the F8U's afterburner-assisted jet engine while on the ground taking off?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-5**	Page 6-10
Solution to this Problem:	Page 6-33	

Problem Workspace

Problem #6.8:

The Foreman of a Machine Shop has his work station located an equal distance from six separate grinders, each of which produces noise at 106 dBA when in operation. What Sound Pressure Level, in dBA, would the Foreman experience if all six grinders were operated simultaneously?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-6**	Pages 6-10 & 6-11
Solution to this Problem:	Page 6-33	

Problem Workspace

Problem #6.9:

The Director of a 20-member bagpipe band experiences a total Sound Pressure Level of 109 dBA when he directs his ensemble. Assuming that every bagpipe produces music (??) at the same sound pressure level as every other one, what must be the Sound Pressure Level of each instrument?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-6**	Pages 6-10 & 6-11
Solution to this Problem:	Page 6-34	

Problem Workspace

Workspace Continued on the Next Page

Continuation of Workspace for Problem **#6.9**

Problem #6.10:

How much longer is an individual, without hearing protection, permitted to work at a location where the noise level has just been reduced from 104 dBA to 92 dBA?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-7**	Page 6-11
Solution to this Problem:	Pages 6-34 & 6-35	

Problem Workspace

Problem #6.11:

Standard ear plugs can reduce the sound of a band saw by 24 dBA. Ear muffs can reduce the sound of this saw by 31 dBA. A Band Saw Operator wearing ear plugs can safely operate her band saw for 4.6 hours per day. If she changes to using ear muffs, for how long a period will she be able to operate her band saw?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-7**	Page 6-11
Solution to this Problem:	Pages 6-35 & 6-36	

Problem Workspace

Problem #6.12:

What is the Daily Dose, expressed as a percentage, for a worker who operates a lathe for 1.5 hours per day, sets his lathe up for 4.5 hours per day, performs administrative tasks for 1 hour per day, and spends the balance of his 8-hour workday either at breaks or eating his lunch? The average noise levels given below were determined by a competent Industrial Hygienist:

Task	Average Sound Pressure Level
Operating the Lathe	95 dBA
Setting up the Lathe	90 dBA
Breaks, Lunch, etc.	84 dBA
Administrative Tasks	82 dBA

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-7**	Page 6-11
	Equation **#6-8**	Page 6-12
Solution to this Problem:	Pages 6-36 & 6-37	

Problem Workspace

Problem #6.13:

What is the Equivalent 8-hour Sound Pressure Level experienced by the Lathe Operator in Problem **#6.12** on the previous page?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-9**	Pages 6-12 & 6-13
Solution to this Problem:	Page 6-37	

Problem Workspace

Problem #6.14:

Four Printers work on a printing production floor where there are three offset presses. The A-Weighted Sound Pressure Levels, as a function of the number of these presses that are in operation, were determined to be as follows:

Number of Presses Operating	Average Sound Pressure Level	Average Daily Time in Operation
0	81 dBA	4.5 hrs
1	93 dBA	2.1 hrs
2	96 dBA	1.0 hrs
3	98 dBA	0.4 hrs

What is the Daily Dose that these Printers are experiencing? Is their Printing Company employer in violation of any OSHA Sound Pressure Level PEL?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-7**	Page 6-11
	Equation **#6-8**	Page 6-12
Solution to this Problem:	Pages 6-37 & 6-38	

Continuation of Workspace for Problem **#6.14**

Problem #6.15:

What is the Equivalent 8-hour Sound Pressure Level experienced by the three Printers listed above in Problem **#6.14**?

Applicable Definitions:	Sound Pressure Level	Pages 6-4 & 6-5
Applicable Formula:	Equation **#6-9**	Pages 6-12 & 6-13
Solution to this Problem:	Page 6-38	

Problem Workspace

Problem #6.16:

A monochromatic tuning fork, operating at "C-below-Middle-C" [for which the frequency is 261 Hz], is observed to produce this tone at an analog Sound Pressure Level of 71 dB, measured on the linear scale. What would a well-calibrated Sound Level Meter, operating on the A-Weighting Scale, indicate as the Sound Pressure Level of this tuning fork?

Applicable Definitions:	Frequency	Page 6-2
	Octave Bands & Bandwidths	Pages 6-2 & 6-3
	Sound Pressure Level	Pages 6-4 & 6-5
	A-Frequency Weighting Scale	Page 6-6
Applicable Formula:	Equation **#6-10**	Page 6-13
Solution to this Problem:	Page 6-38	

Continuation of Workspace for Problem **#6.16**

Problem #6.17:

What are the Upper and Lower Band-Edge Frequencies of the only Octave band on the A-Weighting Scale that does not have a Sound Pressure Level adjustment?

Applicable Definitions:	Frequency	Page 6-2
	Octave Bands & Bandwidths	Pages 6-2 & 6-3
	Sound Pressure Level	Pages 6-4 & 6-5
	A-Frequency Weighting Scale	Page 6-6
Applicable Formula:	Equation **#6-10**	Page 6-13
	Equation **#6-11**	Page 6-14
	Equation **#6-12**	Page 6-14
Solution to this Problem:	Pages 6-38 & 6-39	

Problem Workspace

Problem #6.18:

What is the Center Frequency of the Standard Unitary Octave Band, for which the Lower Band-Edge Frequency is 2,828 kHz? Justify your choice quantitatively.

Applicable Definitions:	Frequency	Page 6-2
	Octave Bands & Bandwidths	Pages 6-2 & 6-3
Applicable Formula:	Equation **#6-11**	Page 6-14
	Equation **#6-12**	Page 6-14
Solution to this Problem:	Page 6-39	

Problem Workspace

Problem #6.19:

What are the Upper and Lower Band-Edge Frequencies of the Standard One Half Octave Band that has a Center Frequency of 354 Hz?

Applicable Definitions:	Frequency	Page 6-2
	Octave Bands & Bandwidths	Pages 6-2 & 6-3
Applicable Formula:	Equation **#6-13**	Pages 6-14 & 6-15
	Equation **#6-14**	Pages 6-14 & 6-15
Solution to this Problem:	Page 6-40	

Continuation of Workspace for Problem **#6.19**

Problem #6.20:

What is the Center Frequency of the Standard One Third Octave Band for which the Lower Band-Edge Frequency is 1,122 Hz?

Applicable Definitions:	Frequency	Page 6-2
	Octave Bands & Bandwidths	Pages 6-2 & 6-3
Applicable Formula:	Equation **#6-15**	Pages 6-15 & 6-16
	Equation **#6-16**	Pages 6-15 & 6-16
Solution to this Problem:	Pages 6-40 & 6-41	

Problem Workspace

SOLUTIONS TO THE SOUND & NOISE PROBLEM SET

Problem #6.1:

To solve this problem, we must use Equation **#6-1**, from Page 6-8:

$$V = 49\sqrt{t + 459} \qquad \text{[Eqn. \textbf{\#6-1}]}$$

$$V_{129°F} = 49\sqrt{129 + 459} = 49\sqrt{588}$$

$$V_{129°F} = (49)(24.25) = 1{,}188.19 \text{ ft/sec}$$

∴ The Speed of Sound at 129°F in the Mojave Desert is 1,188.2 ft/sec.

Problem #6.2:

For the solution to this problem, we must again use Equation **#6-1**, from Page 6-8:

$$V = 49\sqrt{t + 459} \qquad \text{[Eqn. \textbf{\#6-1}]}$$

We must, of course, first convert this temperature, given in relative Metric units, namely, °C, to its corresponding temperature, in relative English units, namely, °F. To do this, we must use **Equation #1-3**, from Page 1-16:

$$t_{Metric} = \frac{5}{9}\left[t_{English} - 32°\right] \qquad \text{[Eqn. \textbf{\#1-16}]}$$

We must now rewrite this expression to solve for the relative English temperature, thus:

$$t_{English} = \frac{9}{5}\left[t_{Metric}\right] + 32°$$

$$t_{English} = \frac{9}{5}(-35°) + 32° = -63° + 32° = -31°F$$

Now that we have the relative English System temperature, we can apply Equation **#6-1**, from Page 6-8:

$$V_{-35°C} = 49\sqrt{(-31° + 459°)} = 49\sqrt{428°}$$

$$V_{-35°C} = (49)(20.69) = 1{,}013.72 \text{ ft/sec}$$

∴ The Speed of Sound at –35°C in Anchorage, AK, is 1,013.7 ft/sec.

Problem #6.3:

This problem relies upon the Definition of an Analog Sound Pressure Level, as listed in Equation **#6-2**, from Page 6-8:

$$L_P = 20\,log\,P + 93.98 \qquad \text{[Eqn. \textbf{\#6-2}]}$$

$$115 = 20\,log\,P + 93.98$$

$$20 \log P = 115 - 93.98 = 21.02$$

$$log\, P = \frac{21.02}{20} = 1.05$$

We next must take the antilogarithm of both sides of this equation, thus:

$$P = 11.25 \text{ nt/m}^2 = 11.25 \text{ Pa}$$

∴ The Analog Sound Pressure that results in a 115 dBA sound = 11.3 Pa.

Problem #6.4:

This solution to this problem relies on the Definition of an Analog Sound Intensity Level, as listed in Equation **#6-3**, from Page 6-9:

$$L_I = 10\, log\, I + 120 \qquad \text{[Eqn. \textbf{\#6-3}]}$$

$$L_I = 10\, log\left(2.45 \times 10^{-7}\right) + 120$$

$$L_I = (10)(-6.611) + 120 = -66.11 + 120 = 53.89 \text{ dB}$$

∴ The Analog Sound Intensity Level of a hovering hummingbird at a distance of 2 meters is 53.9 dB.

Problem #6.5:

This solution to this problem relies upon the Definition of an Analog Sound Power Level, as listed in **Equation #6-4**, from Page 6-9:

$$L_P = 10\, log[P] + 120 \qquad \text{[Eqn. \textbf{\#6-4}]}$$

$$134 = 10\, log[P] + 120$$

$$10\, log[P] = 134 - 120 = 14$$

$$log[P] = \frac{14}{10} = 1.4$$

We next must take the antilogarithm of both sides of this equation:

$$P = 25.12 \text{ watts}$$

∴ The Sound Power of a Top Fuel Dragster (at maximum engine and supercharger RPM) is 25.1 watts.

Problem #6.6:

The solution to this problem will require the use of Equation **#6-5**, from Page 6-10. We must first observe that this aircraft's jet engine is producing sound as a "single hemisphere" radiating source — i.e., since its jet engine can be considered to be “directly on the ground”, it radiates sound only into the air (it is, therefore, only into a “single hemisphere” radiating source); consequently, we must use a directionality factor, **Q = 2**, thus:

$$L_{P\text{-Effective}} = L_{P\text{-Source}} - 20\,log[r] - 0.5 + 10\,log[Q] \qquad \text{[Eqn. \textbf{\#6-5}]}$$

$$L_{P\text{-Effective}} = 165 - 20\,log(300) - 0.5 + 10\,log(2)$$

$$L_{P\text{-Effective}} = 165 - (20)(2.477) - 0.5 + (10)(0.301)$$

$$L_{P\text{-Effective}} = 165 - 49.54 - 0.5 + 3.01 = 117.97 \text{ dBA}$$

∴ The effective Sound Pressure Level experienced by the Ground Observer listed in this problem would be 118 dBA — a very uncomfortably loud sound.

Problem #6-7:

The solution to this problem will also require the use of Equation **#6-5**, from Page 6-10. In this case, we observe that this aircraft's jet engine is producing sound as a "spherical omnidirectional" radiating source — i.e., since the F8U is now airborne, its jet engine is now radiating sound in all directions; consequently, we must use a directionality factor, **Q = 1**, thus:

$$L_{P\text{-Effective}} = L_{P\text{-Source}} - 20\,log[r] - 0.5 + 10\,log[Q] \qquad \text{[Eqn. \textbf{\#6-5}]}$$

$$117.97 = 165 - 20\,log[r] - 0.5 + 10\,log[1]$$

$$20\,log[r] = 165 - 117.97 - 0.5 + (10)(0) = 46.53$$

$$log[r] = \frac{46.53}{20} = 2.33$$

Next taking the antilogarithm of both sides of this equation, we get:

$$r = 212.14 \text{ feet}$$

∴ The F8U will deliver a ~ 118 dBA sound when it is at an altitude of approximately 212 feet directly above the Ground Observer.

Problem #6-8:

This is the classic problem involving the addition of several different quantified (in dBA) noise sources with the goal of obtaining a single overall equivalent noise source. It will require the use of Equation **#6-6**, from Pages 6-10 & 6-11:

$$L_{Total} = 10\,log\left[\sum_{i=1}^{n} 10^{L_i/10}\right] = 10\,log\left[10^{L_1/10} + 10^{L_2/10} + \ldots + 10^{L_n/10}\right] \text{[Eqn. \textbf{\#6-6}]}$$

$$L_{Total} = 10\,log\left[\left(10^{106/10}\right)(6)\right] = 10\,log\left[\left(3.981\times10^{10}\right)(6)\right]$$

$$L_{Total} = 10\,log\left[2.39\times10^{11}\right] = (10)(11.38) = 113.78 \text{ dBA}$$

∴ The Foreman of this Machine Shop will experience noise, at a combined level of 113.8 dBA, from the simultaneous operation of all six grinders.

Problem #6.9:

This problem is completely analogous to Problem **#6.8**; it deals with the combined effect of several different sound sources; it, too, will require the use of Equation **#6-6**, from Pages 6-10 & 6-11:

$$L_{Total} = 10\,log\left[\sum_{i=1}^{n} 10^{L_i/10}\right] = 10\,log\left[10^{L_1/10} + 10^{L_2/10} + \ldots + 10^{L_n/10}\right] \text{ [Eqn. \#6-6]}$$

$$109 = 10\,log\left[(20)\left(10^{L_{Bagpipe}/10}\right)\right]$$

$$log\left[(20)\left(10^{L_{Bagpipe}/10}\right)\right] = \frac{109}{10} = 10.9$$

We next must take the antilogarithm of both sides of this equation, thus:

$$(20)\left(10^{L_{Bagpipe}/10}\right) = 7.943 \times 10^{10}$$

$$10^{L_{Bagpipe}/10} = \frac{7.943 \times 10^{10}}{20} = 3.972 \times 10^{9}$$

Now we must take the common logarithm of both sides of this equation:

$$\frac{L_{Bagpipe}}{10} = 9.599$$

$$L_{Bagpipe} = (10)(9.599) = 95.99 \text{ dBA}$$

∴ Each Bagpipe produces music/noise at approximately 96 dBA.

Problem #6.10:

To answer this question, we must first determine the OSHA permitted duration, in hours, for each of the two identified noise levels. Once this has been accomplished, we simply employ Equation **#6-7**, from Page 6-11, to obtain the requested result:

$$T_{max} = \frac{8}{2^{[L-90]/5}} \qquad \text{[Eqn. \#6-7]}$$

1. For an SPL of 104 dBA:

$$T_{max\ @\ 104\ dBA} = \frac{8}{2^{(104-90)/5}} = \frac{8}{2^{14/5}}$$

$$T_{max\ @\ 104\ dBA} = \frac{8}{2^{2.8}} = \frac{8}{6.964} = 1.149 \text{ hours}$$

2. For an SPL of 92 dBA:

$$T_{max\ @\ 92\ dBA} = \frac{8}{2^{(92-90)/5}} = \frac{8}{2^{2/5}}$$

$$T_{max\ @\ 92\ dBA} = \frac{8}{2^{0.4}} = \frac{8}{1.32} = 6.063 \text{ hours}$$

The additional time permitted at the lesser noise level of 92 dBA, ΔT_{max}, is simply the difference between these two OSHA permitted time intervals; thus:

$$\Delta T_{max} = 6.063 - 1.149 = 4.914 \text{ hours}$$

∴ This individual can spend an additional 4.9 hours (or ~ 4 hours, 54 minutes) at a 92 dBA noise level than would have been permitted at a 104 dBA level.

Problem #6.11:

This problem can be solved by using Equation **#6-7**, from Page 6-11, first to identify the effective equivalent Sound Pressure Level that is being experienced by the Band Saw Operator when she is wearing her ear plugs; then reapply the same relationship to determine the additional time permitted when she uses ear muffs:

$$T_{max} = \frac{8}{2^{[L-90]/5}} \qquad \text{[Eqn. \#6-7]}$$

We must begin by first rearranging this equation so as to solve for the required SPL:

$$2^{[L-90]/5} = \frac{8}{T_{max}}$$

Next, we must take the common logarithm of both sides of this expression:

$$\text{og}\left[2^{[L-90]/5}\right] = \log\left[\frac{8}{T_{max}}\right]$$

$$\log(2)\left(\frac{L-90}{5}\right) = \log(8) - \log(T_{max})$$

$$(0.301)\left(\frac{L-90}{5}\right) = 0.903 - \log(T_{max})$$

$$\frac{L-90}{5} = \frac{0.903 - \log(T_{max})}{0.301}$$

$$L - 90 = \frac{5}{0.301}\left[0.903 - \log(T_{max})\right]$$

$$L = \frac{5}{0.301}\left[0.903 - \log(T_{max})\right] + 90$$

Finally, now, we have an expression that will permit the direct determination of the equivalent "attenuated" band saw SPL (we are dealing here with an attenuated SPL, not the actual operating SPL of the Band Saw). We know the permitted time interval the Operator can work using ear plugs; thus we can determine the effective equivalent SPL she must be exposed to while using her ear plugs, thus:

$$L = \left(\frac{5}{0.301}\right)\left[0.903 - \log(4.6)\right] + 90 = (16.61)(0.903 - 0.663) + 90$$

$$L = (16.61)(0.240) + 90 = 3.992 + 90 = 93.992 \sim 94 \text{ dBA}$$

Therefore, this Band Saw Operator experiences a noise level of 94 dBA while she operates the band saw wearing ear plugs. If she wears ear muffs, she will experience a noise level 7 dBA lower than this level (i.e., there is a 31 dBA reduction with ear muffs vs. 24 dBA reduction with ear plugs). The new reduced noise level will, therefore, become approximately 87 dBA, and the maximum time permitted at this SPL will be given by Equation **#6-7**, from Page 6-11:

$$T_{max} = \frac{8}{2^{[L-90]/5}} \qquad \text{[Eqn. \#6-7]}$$

$$T_{max\ @\ 87\ dBA} = \frac{8}{2^{[87-90]/5}} = \frac{8}{2^{-3/5}} = \frac{8}{0.660} = 12.126 \text{ hours}$$

∴ Using ear muffs, this Band Saw Operator will be able to operate her band saw, without the danger of suffering any hearing loss, for up to 12.1 hours (or ~ 12 hours, 6 minutes) per day.

Problem #6.12:

The solution to this problem will require the use of both Equation **#6-7**, from Page 6-11, and Equation **#6-8**, from Page 6-12, and in that order; thus:

$$T_{max} = \frac{8}{2^{[L-90]/5}} \qquad \text{[Eqn. \#6-7]}$$

1. For an average SPL of 95 dBA:

$$T_{max\ @\ 95\ dBA} = \frac{8}{2^{[95-90]/5}} = \frac{8}{2^{5/5}} = \frac{8}{2} = 4 \text{ hours}$$

2. For an average SPL of 90 dBA:

$$T_{max\ @\ 90\ dBA} = \frac{8}{2^{[90-90]/5}} = \frac{8}{2^{0/5}} = \frac{8}{1} = 8 \text{ hours}$$

3. For an average SPL of 84 dBA:

$$T_{max\ @\ 84\ dBA} = \frac{8}{2^{[84-90]/5}} = \frac{8}{2^{-6/5}} = \frac{8}{0.435} = 18.379 \text{ hours}$$

4. For an average SPL of 82 dBA:

$$T_{max\ @\ 82\ dBA} = \frac{8}{2^{[82-90]/5}} = \frac{8}{2^{-8/5}} = \frac{8}{0.330} = 24.251 \text{ hours}$$

Now with each of these T_{max}s at the various average SPLs, we can apply Equation **#6-8**, from Page 6-12, to obtain the requested result:

$$D = \sum_{i=1}^{n} \frac{C_i}{T_{max_i}} = \frac{C_1}{T_{max_1}} + \frac{C_2}{T_{max_2}} + \ldots + \frac{C_n}{T_{max_n}} \qquad \text{[Eqn. \#6-8]}$$

$$D_{Lathe\ Operator} = \frac{1.5}{4.00} + \frac{4.5}{8.00} + \frac{1}{18.379} + \frac{1}{24.251}$$

$$D_{Lathe\ Operator} = 0.375 + 0.563 + 0.054 + 0.041 = 1.033$$

Now, expressing this result as a percentage, as required by the problem statement, we have:

$$D_{Lathe\ Operator} = 103.3\%$$

∴ This Lathe Operator's daily noise dose, expressed as a percentage, is 103.3%.

Problem #6.13:

The solution to this problem, which is an extension of Problem **#6.12**, requires the use of Equation **#6-9**, from Pages 6-12 & 6-13:

$$L_{equivalent} = 90 + 16.61 \, log[D] \qquad \text{[Eqn. \#6-9]}$$

$$L_{equivalent} = 90 + 16.61 \, log(1.033)$$

$$L_{equivalent} = 90 + (16.61)(0.014) = 90 + 0.234 = 90.234$$

$$L_{equivalent} = 90.234 \text{ dBA}$$

∴ This Lathe Operator experienced an equivalent SPL of ~ 90.24 dBA.

Problem #6.14:

Like Problem **#6.12**, earlier, the solution to this problem will require the use of both Equation **#6-7**, from Page 6-11, and Equation **#6-8**, from Page 6-12, and in that order:

$$T_{max} = \frac{8}{2^{[L-90]/5}} \qquad \text{[Eqn. \#6-7]}$$

1. For an average SPL of 81 dBA, over a duration of 4.5 hours:

$$T_{max\ @\ 81\ dBA} = \frac{8}{2^{[81-90]/5}} = \frac{8}{2^{-9/5}} = \frac{8}{0.287} = 27.858 \text{ hours}$$

2. For an average SPL of 93 dBA, over a duration of 2.1 hours:

$$T_{max\ @\ 93\ dBA} = \frac{8}{2^{[93-90]/5}} = \frac{8}{2^{3/5}} = \frac{8}{1.516} = 5.278 \text{ hours}$$

3. For an average SPL of 96 dBA, over a duration of 1.0 hours:

$$T_{max\ @\ 96\ dBA} = \frac{8}{2^{[96-90]/5}} = \frac{8}{2^{6/5}} = \frac{8}{2.297} = 3.482 \text{ hours}$$

4. For an average SPL of 98 dBA, over a duration of 0.4 hours:

$$T_{max\ @\ 98\ dBA} = \frac{8}{2^{[98-90]/5}} = \frac{8}{2^{8/5}} = \frac{8}{3.031} = 2.639 \text{ hours}$$

Now with these four T_{max}s at each of the various average SPLs, we can apply Equation **#6-8**, from Page 6-12, to obtain the requested result; thus:

$$D = \sum_{i=1}^{n} \frac{C_i}{T_{max_i}} = \frac{C_1}{T_{max_1}} + \frac{C_2}{T_{max_2}} + \ldots + \frac{C_n}{T_{max_n}} \qquad \text{[Eqn. \#6-8]}$$

$$D_{Printer} = \frac{4.5}{27.858} + \frac{2.1}{5.278} + \frac{1.0}{3.482} + \frac{0.4}{2.639}$$

$$D_{Printer} = 0.162 + 0.398 + 0.287 + 0.152 = 0.998$$

Now, expressing this result as a percentage as required by the problem statement, we have:

$$D_{Printer} = 98.82\%$$

∴ These Printers' daily noise dose expressed as a percentage = 99.8%.

& The Printing Company that employs these four Printers is not in violation of any established OSHA SPL dosage standards.

Problem #6.15:

The solution to this problem, which is an extension of Problem **#6.14**, will require the use of Equation **#6-9**, from Pages 6-12 & 6-13:

$$L_{equivalent} = 90 + 16.61\,log[D] \qquad \text{[Eqn. #6-9]}$$

$$L_{equivalent} = 90 + 16.61\,log(0.998)$$

$$L_{equivalent} = 90 + (16.61)(-0.001) = 90 - 0.013 = 89.987 \sim 90\text{ dBA}$$

∴ These Printers experience an equivalent SPL of ~ 90 dBA.

Problem #6.16:

The solution to this problem requires only the Descriptive Definition of the A-Frequency Weighting Scale Factors, as shown in the Tabulation associated with Equation **#6-10**, from Page 6-13. Clearly this note ("C-below-Middle-C" — reference the piano scale) falls into the 250-Hz Octave Band. For this Octave Band, we must deduct 9 dB from every identified Linear Sound Pressure level; therefore:

∴ The SPL of this "C-Below-Middle-C" Tuning Fork = 71 dB_{Linear} = 62 dBA.

Problem #6-17:

Again from the Descriptive Definition of the A-Frequency Weighting Scale Factors, as shown in the Tabulation associated with Equation **#6-10**, from Page 6-13, we can see that the only Octave Band that does not have a SPL adjustment is the 1,000-Hz Octave Band. To determine the Upper and Lower Band-Edge Frequencies, we must employ the following two Equations, namely, Equation **#s 6-11** & **6-12**, both from Page 6-14:

$$f_{upper-1/1} = 2f_{lower-1/1} \qquad \text{[Eqn. #6-11]}$$

$$f_{center-1/1} = \sqrt{\left[f_{upper-1/1}\right]\left[f_{lower-1/1}\right]} \qquad \text{[Eqn. #6-12]}$$

Combining these two expressions, we obtain the useful relationship shown below:

$$f_{center-1/1} = \sqrt{\left[2f_{lower-1/1}\right]\left[f_{lower-1/1}\right]} = \sqrt{2}\left(f_{lower-1/1}\right)$$

Now, solving for the Lower Band-Edge Frequency, given the Center Frequency, we get:

$$f_{lower-1/1} = \frac{f_{center-1/1}}{\sqrt{2}} = \frac{\sqrt{2}}{2}\left(f_{center-1/1}\right)$$

Now, substituting in the known values, we get:

$$f_{lower-1/1} = \frac{\sqrt{2}}{2}(1,000) = (0.707)(1,000) = 707.1 \text{ Hz}$$

And since we know from Equation **#6-11** that the Upper Band-Edge Frequency is twice the Lower Band-Edge Frequency, we can obtain the final result asked for in the problem statement:

$$f_{upper-1/1} = 2f_{lower-1/1} \qquad \text{[Eqn. \#6-11]}$$

$$f_{upper-1/1} = 2\left(f_{lower-1/1}\right) = 1,414.2 \text{ Hz}$$

∴ The Upper and Lower Band-Edge Frequencies of the 1,000-Hz Standard Unitary Octave Band are as follows:

Upper Band-Edge Frequency = 1,414 Hz

Lower Band-Edge Frequency = 707 Hz

Problem #6.18:

To develop the solution for this problem, we must employ the following two Equations, namely, Equation **#s 6-11** & **6-12**, both from Page 6-14. In this case, we must determine the Center Frequency of a Full Octave Band for which we know only the Lower Band-Edge Frequency.

$$f_{upper-1/1} = 2f_{lower-1/1} \qquad \text{[Eqn. \#6-11]}$$

$$f_{center-1/1} = \sqrt{\left[f_{upper-1/1}\right]\left[f_{lower-1/1}\right]} \qquad \text{[Eqn. \#6-12]}$$

Again combining these two relationships, as was the case for Problem **#6.17**, we can develop the following equation:

$$f_{center-1/1} = \sqrt{2}\left(f_{lower-1/1}\right)$$

Now, substituting in the known value for the Lower Band-Edge Frequency, we can directly determine the Center Frequency, thus:

$$f_{center-1/1} = \sqrt{2}(2,828) = 3,999.4 \sim 4,000 \text{ Hz}$$

∴ The Center Frequency of this Full Octave Band is 4,000 Hz (rounding up from the result of 3,999.4 Hz). This is the Standard 4,000 Hz = 4 kHz Octave Band.

Problem #6.19:

To solve this problem, we will have to apply the two Equations that make up the relationships for Half Octave Bands, namely, Equation **#s 6-13** & **6-14**, from Pages 6-14 & 6-15:

$$f_{upper-1/2} = \left(\sqrt{2}\right)\left(f_{lower-1/2}\right) \qquad \text{[Eqn. \#6-13]}$$

$$f_{center-1/2} = \sqrt{\left(f_{upper-1/2}\right)\left(f_{lower-1/2}\right)} \qquad \text{[Eqn. \#6-14]}$$

Again combining these two relationships, as was the case for Problem **#s 6.17** & **6.19**, we get the following useful equation:

$$f_{center-1/2} = \sqrt{\left(f_{lower-1/2}\right)\left(\left[\sqrt{2}\right]\left[f_{lower-1/2}\right]\right)} = \left(f_{lower-1/2}\right)\sqrt{\sqrt{2}} = \left(f_{lower-1/2}\right)\sqrt[4]{2}$$

We can rearrange this relationship to solve for the Lower Band-Edge Frequency:

$$f_{lower-1/2} = \frac{f_{center-1/2}}{\sqrt[4]{2}}$$

Using this relationship, we can solve directly for the Lower Band-Edge Frequency of this Half Octave Band:

$$f_{lower-1/2} = \frac{354}{\sqrt[4]{2}} = \frac{354}{1.189} = 297.7 \text{ Hz}$$

With the Lower Band-Edge Frequency known, we can use Equation **#6-13**, from Pages 6-14 & 6-15, to calculate the required Upper Band-Edge Frequency directly:

$$f_{upper-1/2} = \left(\sqrt{2}\right)\left(f_{lower-1/2}\right)$$

$$f_{upper-1/2} = \left(\sqrt{2}\right)(297.7) = 421.0 \text{ Hz}$$

∴ The Upper and Lower Band-Edge Frequencies of the 354-Hz Standard Half Octave Band are as follows:

Upper Band-Edge Frequency ~ 421 Hz

Lower Band-Edge Frequency ~ 298 Hz

Problem #6.20:

To solve this problem, we will have to apply the two Equations that make up the relationships for any 1/nth Octave Bands, as shown in Equation **#s 6-15** & **6-16**, from Pages 6-15 & 6-16, respectively. We must start out by determining the Upper Band-Edge Frequency for this 1/3rd Octave Band; using Equation **#6-15**:

$$f_{upper-1/n} = \sqrt[n]{2}\left(f_{lower-1/n}\right) \qquad \text{[Eqn. \#6-15]}$$

Using this relationship we can directly determine the Upper Band-Edge Frequency for this 1/3rd Octave Band:

$$f_{upper-1/3} = \sqrt[3]{2}\left(f_{lower-1/3}\right) = \sqrt[3]{2}(1{,}122) = (1.26)(1{,}122) = 1{,}413.6 \text{ Hz}$$

Finally, now we can apply Equation **#6-16** to determine the requested Center Frequency of this 1/3rd Octave Band:

$$f_{center-1/n} = \sqrt{\left(f_{upper-1/n}\right)\left(f_{lower-1/n}\right)} \qquad \text{[Eqn. \#6-16]}$$

$$f_{center-1/3} = \sqrt{(1,122)(1,413.6)} = \sqrt{1,586,094.5} = 1.259.4 \text{ Hz}$$

∴ The Standard 1/3rd Octave Band, for which the Lower Band-Edge Frequency is 1,122 Hz, has a Center Frequency of 1,259 Hz.