CHAPTER 2

REVIEWS ON INDUSTRIAL NOISE AND ENERGY EXPENDITURE

This chapter begins with the basic knowledge for noise criterion. Then, the second section provides related information for energy criterion.

2.1 Industrial Noise

In this section, the ergonomics background on industrial noise control is reviewed. How to measure the noise level is also described. The safe noise limit for every worker, which is usually recommended to be equal to an 8-hour time-weighted average (TWA) of 90 dB*A*, is defined.

2.1.1 Measures of Noise Levels

In an environment where there are multiple noise sources, such as noisy machines, the noise level at a particular location in that environment is the sum of the noise levels from all noise sources, including the ambient noise level The combined noise level $\overline{L}_i$ at location *i* can be analytically determined from

$$\overline{L}_i = 10 \log\left(10^{\left(\frac{L_{ab}-120}{10}\right)} + \sum_{j=1}^{n} \frac{10^{\left(\frac{L_j-120}{10}\right)}}{d_{ij}^2} \right) + 120 \tag{2.1}$$

where L_{ab} is the ambient noise level (in dB*A*), L_j is the noise level (in dB*A*) of machine *j* measured at a one-meter distance from the machine, and d_{ij} is the Euclidean distance (in meters) between location *i* and machine *j*.

2.1.2 Permissible Noise Exposure Limits

Since it may not be practical to require machine manufacturers to design and build industrial machines that do not generate loud noise during operation, one way to make sure that workers will not be exposed to the noise hazardous condition for too long is to limit the exposure time.

The Occupational Safety and Health Administration (OSHA), the US government agency that is responsible for health and safety in the workplace, has established permissible noise exposure for industrial workers (OSHA 1983). The permissible levels depend on the exposure duration such that the louder the noise level, the shorter the duration of exposure (as shown in Table 2.1)

It should be noted that an exposure to noise level below 80 dB*A* is not considered as hazardous and does not require a time limit. Additionally, exposure above 115 dB*A* is not permitted regardless of duration.

Table 2.1 Permissible Noise Exposures (OSHA, 1983)

Noise Level (dBA)	Permissible Time (Hour)
80	32
85	16
90	8
95	4
100	2
105	1
110	0.5
115	0.25

Two measures of noise exposure are widely used to their simplicity and practicality. They are (1) a daily noise dose, and (2) an 8-hour time-weight average sound level. These noise exposure measures account for both the sound noise level and the exposure duration. Since workers do not generally stay in one work area throughout the entire day, it is thus necessary to determine the daily exposure to noise and check if it exceeds the permissible level.

Daily Noise Dose: From the fact that exposure to any noise level at or above 80 dBA causes the worker to receive a partial dose of noise, the daily noise dose then is equal to the sum of the partial doses. A partial dose is defined as the ratio of time actually spent at noise level to the maximum permissible time at noise level (determined from Table 2.1.) The daily noise dose D_T (in percent) can be calculated from

$$D_T = 12.5 \sum_{j=1}^{n} C_j \left[2^{\frac{\bar{L}_j - 90}{5}} \right] \qquad (2.2)$$

where C_j is the length of time (in hours) that the worker operates at Machine j, and $\bar{L}_j$ is the combined noise level (dBA) at Machine j. A noise dose of 100 percent is designated as the permissible noise exposure level.

8-hour Time-Weighted Average Sound Level: An 8-hour time-weighted average (TWA) sound level is the sound level that the worker was exposed to that sound level continuously over an 8-hour working day. TWA can be determined from the following formula.

$$\text{TWA} = 16.61 \left[\log \left(\sum_{j=1}^{n} \frac{C_j}{8} \left(2^{\frac{\bar{L}_j - 90}{5}} \right) \right) \right] + 90 \qquad (2.3)$$

It can be proved that a noise dose of 100 percent is equivalent to a TWA of 90 dBA. Thus the 90-dBA TWA is also the permissible noise exposure level.

Suppose that a worker has been assigned to perform 3 tasks in an 8-hour day. The noise levels measured at each task are 91, 95, and 88 dBA, respectively. Also, the work durations at each task are 2, 2, and 4 hours, respectively. That is, $n = 3$; $C_1 = 2$, $C_2 = 2$, $C_3 = 4$; $\bar{L}_j$ is 91, 95, and 88 dBA for each j. Thus an 8-hour TWA of this worker is calculated by using Equation 2.3 then equals to 91.11 dBA, which exceeds the daily permissible noise exposure.

2.1.3 Industrial Noise Control

If the analysis of noise exposure indicates that workers are exposed to high noise levels, a noise control program must be initiated to reduce the workplace noise levels. However, most people only use the hearing protection devices like earplugs as their noise control program. While the cost of earplug method is attractively cheap but its effectiveness is usually the poorest among other noise control. The noise reduction ratings (NRR) tend to be overly stated by manufacturer (Gasaway, 1984). Wilson et al. (1981) reported that workers typically adjust their hearing protection devices for comfort rather than to achieve maximum attenuation. In many manufacturing facilities, workers choose not to wear hearing protection devices unless strictly enforced and routinely monitored. Comfort seems to be a major factor that influences whether or not the hearing protection devices are worn by workers (Casali et al., 1987). In fact, the most direct and perhaps effective approach is to reduce the noise levels at the three parts of the noise problem. They are: source, path, and receiver. Noise reduction can be accomplished using engineering and administrative control.

Engineering noise controls require careful analysis on both a practical and economic basis. Successful implementation of engineering controls needs individuals who are highly proficient in this field. Competent external consultants may be contracted to provide services if in-house highly specialized personnel are not available. Examples of engineering controls are as follows.

- Provide proper maintenance to existing machines.
- Substitute noisy machines or machine parts with quieter ones.
- Substitute noisy processes with quieter ones.
- Eliminate or reduce machine vibrations.
- Enclose noisy machines if practical.
- Isolate noisy machines from areas where workers are present.
- Use barriers (solid or transparent) to block direct paths between noisy machines and workers

In several situations, engineering controls may be infeasible or inadequate for reducing the noise level to the permissible limit. Administrative control techniques should then be applied in conjunction with the above-mentioned engineering controls. List below are some of the widely applied administrative noise controls.

- Conduct noise survey of the workplace and construct a noise contour map to identify noise hazardous areas.
- Enforce the use of hearing protection devices when working in noise hazardous areas.
- Conduct an industrial audiometric program to monitor the effect of workplace noise on workers.
- Transfer or assign workers from a work area with high noise level to another area with a lower one.
- Reschedule machine-operating times so as to reduce the number of workers exposed to loud noise.

Most of this study concerns on transferring or rescheduling workers, or frequently called *job rotation*, so that they are less exposed to high noise level. Job rotation is the administrative control that compromises between safety concern and cost effectiveness (Olishifski and Standard, 1988). While most administrative noise controls seem to be simple, it is found that some could be difficult to implement especially when the maximum effectiveness is to be achieved. Job rotation is a good example of an administrative control that appears to be simple yet is difficult to optimally implement. Briefly, job rotation requires workers to rotate among tasks within one workday in order to reduce their daily noise exposures. In a few special situations, job rotation has not only significantly reduced the worker's TWA but also increased productivity by sharing very demanding tasks among workers (Royster and Royster, 2003). In practice, the number of workstations that individual workers will operate, work duration at each workstation, and the order of assignment must be defined. Since the objective is to reduce workers' noise exposures, it is necessary to search for the feasible set of work assignments such that none of the workers receives the noise exposure more than 90 dB*A*. In a case that there is no feasible set of work assignments with the current number of available workers, the number of workers must be increased. However, the number of workers exposed to high noise levels should be minimal (NIOSH, 1998).

2.2 Energy Expenditure

Industrial workers are often required to expend moderate to high level of physical energy to perform their assigned tasks such as lifting/lowering, carrying, and loading/unloading. Thus, they are likely to develop excessive fatigue, which can cause occupational accidents and over-exhaustion after work. The management and plant engineers should evaluate the daily energy expenditure of workers. An individual worker should not expend the daily energy more than his or her energy limit.

In this section, the concept of work physiology is briefly introduced. Next, the existing methods to measure energy expenditure (or metabolic rate) of any individual are described. Then, the practical methods for measuring the energy expenditure of industrial job are presented. Lastly, the recommended limits of the working energy capacity are summarized. In this study, 33 % of maximum oxygen uptake of any worker is used as his or her working energy capacity. Thus, the limit of working energy capacity differs in each person. In contrast, a TWA of 90 dB*A* is the recommended noise limit for every person.

Work physiology is the study of the functions of the human organisms affected by muscular work stresses. Workers should not develop excessive fatigue at the end of the day, so that they can recover and be ready to work on the next day. When a worker performs a task, his muscle is contracted. Energy is required for this contraction activity. The sources of energy are carbohydrates and fats (or protein during severe malnutrition), which will be transformed into nutrients conveyed in blood vessels. Oxygen, delivered from lung, is also required to convert nutrients to energy. Nutrients and oxygen, mixed into bloods, are pumped by heart to reach muscle. Metabolism is the chemical process of the conversion of nutrients and oxygen into mechanical work and heat.

At initial state, human body cannot instantly supply oxygen to muscle, thereby building up lactic acid. This buildup of lactic acid causes fatigue in muscle. Until his body reaches steady state, oxygen is then available and used in metabolic processes. As a result, Carbon Dioxide is produced instead of lactic acid, and released through lung. When the worker finishes his work, the body is in recovery state. However, the body still continues to supply oxygen to muscle for the oxygen deficit occurred during the initial state. Basal metabolism rate (BMR) is the metabolic rate that keeps a human body alive and functioning, but not performing any external work.

2.2.1 Assessment of Energy Expenditure

The most accurate and direct method to assess the energy expenditure of a person is the *Direct Calorimetry* method. This method is simple to understand but difficult to perform. The subject (or individual) is placed in a closed, well-insulated chamber known as a calorimeter. If allowance is made for the heat content of everything entering and leaving the chamber (food, excreta, air, etc), the heat content measured by the temperature changes in water flowing through the calorimeter, reflects the energy expenditure expended by the subject. This is an excellent method in that it measures heat production directly. But the subject must be confined inside the chamber for a long period of time, which is impractical in most situations. Calorimeters are found in only a few research laboratories.

Another method that is more frequently used is the *Indirect Calorimetry* methods. In this method, a person's oxygen consumption while performing work can be used as a measure of his or her metabolic energy production. One simply measures the subject's *oxygen uptake* per unit time by measuring total ventilation and the oxygen content of both inspired and expired air. From this value one calculates heat content based on the principle that 1 liter (L) of oxygen required in the oxidation of nutrients equals to an energy expenditure of approximately 5.0 kcal. One can now calculate the energy conversion occurring in the body from the volume of oxygen consumed.

In fact circulatory and metabolic processes interact closely. Nutrients and oxygen must be brought to the muscle. Thus, the heart rate, as a primary indicator of circulatory functions, and oxygen consumption have a linear and reliable relationship in the range between light and heavy work. If this relationship is determined as a linear equation by regression method, heart rate, which can be assessed easily in beat per minute (bpm) using measurement devices, is substituted by oxygen uptake in L/m, which can then be converted to the energy cost in kcal/m.

To properly match a worker to a job, the energy capacity of the worker and the energy capacity required in the job must be known. The energy capacity is determined from the *maximal aerobic power* of the worker, which is his maximal oxygen uptake during the steady state (i.e., the energy capacity required in the job is the workload of the job performed by a *standardized* worker.)

A standardized worker is generally unavailable; the worker who actually performs the job then represents a standardized subject under the assumption that he is physically normal. Methods of measuring a worker's maximal aerobic power can be direct or indirect.

For direct measurement, the maximal oxygen uptake is the highest oxygen uptake attainable in the subject, i.e., a further increase in workload will not result in an increase in oxygen uptake. The subject will be test until he or she cannot continue to perform the workload and become exhausted. The workload is started at a safe low level and is then increased either continuously or intermittently until the maximum oxygen uptake is reached. Most common physical tests representing workloads are cycling on an ergometer, running on a treadmill, or stepping up and down on a steptest. The heart rate at the maximum oxygen uptake is approximately 220 – age. This method is not generally used in industries due to its unsafe effect. However, it is more accurate and suitable for physically fit and young subjects. There are also several indirect methods of estimating the maximal oxygen uptake, which are described as follows.

- **Regression method:** this indirect method is based on the following two factors: the linear relationship between heart rate and oxygen uptake, and an age-dependent expected maximal heart rate or 220 – age. In measuring oxygen consumption, an oxygen analyzer is needed. Heart rate is normally measured with a heart rate monitor in beats per minute (bpm). At least three steady-state submaximal data sets of oxygen uptake (L/m) and heart rate (bpm) should be obtained. Once the three or more pairs of oxygen uptake and heart rate have been obtained, linear regression can be used to predict maximal oxygen uptake. Let y be the oxygen uptake (L/m) and x be the heart rate (bpm). A linear relationship is $y = mx + c$. Once the regression equation has been established, the maximal oxygen uptake can be estimated by using the predicted maximal heart rate (i.e., x_{max} = 220 – age) in the regression equation and solving for the maximal oxygen uptake, or y_{max}.

- **Astrand-Astrand nomogram:** this method was first proposed by Astrand (1960) and further elaborated in Astrand and Rodahl (1986), and Rodahl (1989). It is based on submaximal measurements of oxygen uptake and heart rate. The nomogram is used along with an age-correction factor. However, one, who has not been trained sufficiently, can have difficulty reading the nomogram and may extract incorrect data from it. This was corrected by Tayyari and Ramsey (1985) by proposing the use of a simplified equations based on the nomogram.

- **Step test**: this method is frequently used when an oxygen analyzer is unaffordable proposed by Sigconolfi et al. (1985). A subject needs to perform the test on a steptest with known height and frequency of steps. His method uses an equation to estimate the submaximal oxygen uptake obtained from the ASCM guidelines (American College of Sports Medicine, 1991). And also the subject's heart rate at steady state must be measured. Then the maximal oxygen uptake can be predicted using the Astrand-Astrand nomogram,

- **Teyyari's conventional method:** (Tayyari and Smith, 1997) A conventional method was introduced (Tayyari, 1995) which predicts y_{max} based on the person's body weight and measured heart rate during walking on a treadmill. This method also has an simplified equation.

Other indirect measurements of estimating the maximal oxygen uptake are such as Doubly Labeled Water (Metabolic Solutions Inc, 2002), which measure the difference between the oxygen elimination rate of water intake and urine collection.

2.2.2 Assessment of Energy Requirement

Most accurate method to assess the energy of a job is the direct measurement by indirect calorimetry. The oxygen uptake will be measured while the standardized worker performing the work in question. This method is accurate but representing the energy expenditure for the time period that the expired air is collected (usually in a matter of minutes). Moreover, the equipment used for the collection of the expired air may restrict the worker's performance. The subject may also deny wearing nose clip or the mouthpiece, necessary for the expired air collection. The frequently used measuring devices are such as Douglas bag and Oxylog. The example of detailed calculation from the oxygen uptake to energy expenditure can be found in ISO8996 (ISO, 1990).

Easier method than indirect calorimetry is to estimate oxygen uptake on the basis of recorded heart rate. This method uses a linear relationship between the oxygen uptake and heart rate obtained from a worker's sub-maximal exercise test. Then let the worker perform the actual work and measure his heart rate. The oxygen uptake at actual work can then be estimated using a linear equation acquired from the regression method. Note that the linear relation ship between the oxygen uptake and heart rate holds only when the large muscle groups are engaged in the actual work. However, Rodahl et al. (1974) checked the accuracy of the oxygen uptake measured from a classical Douglas bag method and compared the results with the oxygen uptake estimated from the simultaneously recorded heart rate in six commercial fisherman while engaged in coastal fishing. The difference was less than ±15 percent.

Another simpler method but less accurate is to classify the typical activities with known energy expenditure. For 24 hours, the subject or an observer keeps a detailed diary of activities. These activities are classified according to standard semantic descriptions such as light sitting, light standing, etc. The total time spent in each category is obtained and an estimate of the total oxygen uptake made based upon values of oxygen uptake assigned to each of the semantic descriptions. The detailed tables of energy expenditure of each semantic description can be found in ISO8996 (ISO, 1990).

One interesting method is to let the subject rate their perceived effort. Borg (1962) developed a category scale for the rating of perceived exertion. The scale ranges from 6 to 20 (to match heart rates from 60 to 200 bpm), with every second number anchored by verbal expressions. Later, Borg (1982) proposed the modification of his scale.

2.2.3 Recommended Limits

Various recommendations of working energy capacity can be found in the literature (Lehnmann, 1958; Michael et al., 1961; Blink ,1962; Tayyari, 1987; Grandjean, 1988; and Ayoub and Mital, 1989.) However, for this study, the NIOSH limit, or 33% of maximum oxygen uptake is used as the limit of working energy capacity in an 8-hour workday (NIOSH, 1981). Because the percentage of 33 is safer than many recommended limits and since the maximum oxygen uptake of any worker must be individually identified; thus this limit has no bias over a group of people with differences in age, sex, or physical fitness.