10 Safety in Engineering Maintenance

10.1 INTRODUCTION

Each year billions of dollars are being spent worldwide to keep engineering systems functioning effectively. The problem of safety in engineering maintenance has become an important issue because of the occurrence of various maintenance-related accidents throughout the industrial sector. For example, in 1994, in the U.S. mining sector approximately 14% of all accidents were associated with maintenance activity [1]. Since 1990, the occurrence of such accidents has been following an increasing trend [1].

The problem of safety in the area of engineering maintenance involves ensuring not only the safety of maintenance personnel but also the safety of actions taken by these individuals. Engineering maintenance activities present many unique occupation-related hazards, including performing tasks at elevated heights or with equipment/system that has significant potential for releasing mechanical or electrical energy.

All in all, engineering maintenance must strive to control or eradicate potential hazards for ensuring proper protection to individuals and material, including items such as electrical shocks, high noise levels, toxic gas sources, moving mechanical assemblies, and fire radiation sources [2, 3].

This chapter presents various important aspects of safety in engineering maintenance.

10.2 FACTS, FIGURES, AND EXAMPLES

Some of the important facts, figures, and examples that are directly or indirectly concerned with maintenance safety are presented below.

- In 1993, there were around 10,000 work-related deaths in the United States [1].
- In 1998, about 3.8 million workers suffered from disabling injuries on the job in the United States [1, 4].
- In 1994, approximately 14% of all accidents in the United States mining sector were associated with maintenance activity [1, 2].
- In 1998, the total cost of work-related injuries in the United States was estimated to be around $125 billion [1, 2, 4].
- A study of safety issues concerning onboard fatalities in jet fleets worldwide for the period 1982–1991 reported that maintenance and inspection was the second most important issue with 1481 onboard fatalities [5, 6].
- In 1985, 520 people were killed in a Japan Airlines Boeing 747 jet accident because of an incorrect repair [7, 8].

- In 1991, four workers were killed in an explosion at an oil refinery in Louisiana as three gasoline-synthesizing units were being brought back to their operating state, after going through some maintenance-related activities [9].
- In 1990, 10 people were killed on the USS *Iwo Jima* (LPH2) naval ship because of a steam leak in the fire room, after maintenance workers repaired a valve and replaced bonnet fasteners with mismatched and incorrect material [10].
- In 1979, 272 people were killed in a DC-10 aircraft accident in Chicago because of wrong procedures followed by maintenance workers [11].

10.3 CAUSES OF MAINTENANCE SAFETY PROBLEMS AND FACTORS RESPONSIBLE FOR DUBIOUS SAFETY REPUTATION IN MAINTENANCE ACTIVITY

Over the years various causes for safety problems have been identified. Some of the important ones are poor safety standards, poor work environment, poor work tools, poor training of maintenance personnel, poorly written instructions and procedures, poor management, and insufficient time to perform required maintenance tasks [2, 4].

There are many factors responsible for giving the maintenance activity a dubious safety reputation. Some of these are presented below [12].

- Performance of maintenance activities underneath or inside items such as air ducts, pressure vessels, and large rotating machines.
- Difficulty in maintaining effective communication with individuals involved in the performance of maintenance tasks.
- Sudden need for maintenance work, thus allowing a very short time for appropriate preparation.
- Disassembling previously operating equipment, thus carrying out tasks subject to the risk of releasing stored energy.
- Performance of maintenance activities in remote areas, at odd hours, and in small numbers.
- Need to carry heavy and rather bulky objects from a store/warehouse to the maintenance location, sometimes utilizing lifting and transport equipment that is way beyond the boundaries of a strict maintenance regime.
- Maintenance work performed in unfamiliar surroundings or territory imply that hazards such as missing gratings, rusted handrails, and damaged light fittings may go totally unnoticed.
- From time to time, maintenance activities may require performing tasks such as disassembling corroded parts or manhandling difficult heavy units in rather poorly lit areas and confined spaces.
- Frequent occurrence of many maintenance tasks (e.g., equipment failures), thus lesser opportunity for discerning safety-related problems and for initiating appropriate remedial actions.

10.4 FACTORS INFLUENCING SAFETY BEHAVIOR AND SAFETY CULTURE IN MAINTENANCE PERSONNEL

There are many factors that influence safety behavior and safety culture in maintenance personnel. For example, some of the factors that influence safety behavior and safety culture in railway maintenance workers are as follows [13]:

- Poor and underutilized real-time risk assessment skills
- Communication on the job (poor quality and excessive)
- Individual perception of what "safe" is
- Management personnel's communication methods
- Feedback messages from management personnel
- Physical conditions
- Supervisory personnel's visibility and accessibility
- Volume of paper work
- Reporting methods
- Equipment (condition, appropriateness, and availability)
- Competence capability and certification
- Fatigue, concentration, and ability to function
- Peer pressure
- Practical alternatives to rules
- Inconsistent teams
- Contradictory rules
- Perceived objective of the rule book
- Rule dissemination
- Training methods and training needs analysis
- Safety role model behavior
- Perceived purpose of paper work
- Pre-job information dissemination
- Rule book usability and availability
- Social pressure of home life

10.5 GOOD SAFETY-RELATED PRACTICES DURING MAINTENANCE WORK AND MAINTENANCE-RELATED SAFETY MEASURES CONCERNING MACHINERY

It is very important to follow good practices before, during, and after maintenance operations because of the existence of various types of hazards. Failure to follow good practices during any phase of maintenance can lead to potentially hazardous conditions. Four good safety-related practices to be followed during maintenance work are as follows [14].

- **Prepare for Maintenance during the Design Phase**
  It basically means that preparation for maintenance actually starts during the design of the facility by ensuring that appropriate indicators are in place for allowing effective troubleshooting and diagnostic work. Furthermore,

the equipment is designed so that normal safety-related measures can easily be taken before the maintenance activity. More specifically, equipment is designed so that all appropriate safeguards are in place for allowing it to be drained, purged, isolated, and analyzed effectively.

- **Prepare All Staff Members for Maintenance Operations**
  Usually maintenance activity involves opening equipment that contains hazardous material during its normal operations. Thus, it is important to take necessary precautions prior to working on such equipment to ensure that it is completely free from residual material and is at a safe temperature and pressure. Often equipment is prepared for maintenance by people other than those actually performing maintenance on the equipment.

  In this scenario, it is essential to prepare all staff members (i.e., who prepare the equipment for maintenance and the others who perform maintenance) for maintenance operations.
- **Highlight All Potential Hazards and Plan Effectively Well in Advance**
  There is no substitute for proper job planning as effective equipment isolation prior to the maintenance activity starts with thorough preplanning. Also, good practice guidelines clearly state that all potential hazards are most effectively recognized during the planning process, rather than during the job execution in a stressful environment.

  In summary, ensure that the equipment under consideration is properly freed from all types of potential hazards and that all safety precautions can be satisfied effectively. In situations when procedures cannot be followed effectively and/or safety precautions cannot be fully satisfied, do not proceed any further until a proper hazard evaluation can be carried out and a safe course of measures determined.
- **Plan Now for the Future**
  This is concerned with analyzing the potential effects on the maintenance activity when changes are made to the existing process. Along with the determination of how operations will be affected, process management must carefully evaluate questions such as: Will there be need for more frequent or less frequent maintenance? Will maintenance personnel be at greater risk because of this change? and How will this change affect all the future maintenance-related activities?

  Over the years safety specialists have done much to point out various safety measures to be observed in working around machinery, particularly with respect to the maintenance activity. Past experiences indicate that all of these and the application of careful planning have considerably reduced the occurrence of accidents and damage to machinery. The following maintenance-related safety measures have proven to be very useful [15]:

  - All types of machines properly equipped with appropriate safety valves, alarms for indicating abnormal operating conditions, and over-speed cutouts
  - Appropriate guards around exposed moving parts of machining equipment

- Platforms, ladders, and stairways with appropriate protective features
- Safety shoes, hats, gloves, and clothing
- Items such as portable electric drills, grinders, and electric motors should have proper ground wire attached to prevent maintenance workers and others coming in contact with defective wiring on machining equipment
- Equipment designed for work intended should an appropriate level of safe margin for insuring safe operation under extreme environments
- Safe tools for clipping and grinding and appropriate goggles for eye protection
- All types of electrical equipment installed according to currently approved code

10.6 MAINTENANCE SAFETY-RELATED QUESTIONS FOR ENGINEERING EQUIPMENT MANUFACTURERS

Engineering equipment manufacturers can play a key role in improving maintenance safety during equipment field use by effectively addressing common problems that might be encountered during the maintenance activity. Questions such as the ones presented below can be quite useful to equipment manufacturers in determining whether the common problems that might be encountered during the equipment maintenance activity have been addressed properly [16].

- Are all the test points located at easy to find and reach locations?
- Are the components requiring frequent maintenance easily accessible all the time?
- Are effectively written instructions available for repair and maintenance activities?
- Can the disassembled piece of equipment for repair be reassembled incorrectly so that it becomes hazardous to all potential users?
- Were human factors principles properly applied to reduce maintenance problems?
- Is the repair process hazardous to all involved repair workers?
- Do the repair instructions contain effective warnings to wear appropriate gear because of pending hazards?
- Are warnings properly placed on parts that can shock maintenance personnel?
- Is the need for special tools for repairing safety-critical parts reduced to a minimum level?
- Is there a proper system to remove hazardous fluid from the equipment/system to be repaired?
- Does the equipment contain proper safety interlocks that must be bypassed for performing essential repairs/adjustments?
- Is the equipment/system designed in such a way that after a failure, it would automatically stop operating and would cause absolutely no damage?
- Does the equipment contain an appropriate built-in system to indicate that safety-critical parts need maintenance?

- Do the instructions include warnings for alerting maintenance personnel of any danger?
- Is there an appropriate mechanism installed for indicating when the backup units of safety-critical systems fail?
- Was proper attention given to reducing voltages to levels at test points so that hazards to maintenance workers are reduced?

10.7 GUIDELINES FOR ENGINEERING EQUIPMENT DESIGNERS TO IMPROVE SAFETY IN MAINTENANCE

Over the years, professionals working in the area of maintenance have developed various guidelines for engineering equipment designers, considered useful to improve safety in maintenance. Some of these guidelines are presented below [16].

- Pay close attention to typical human behaviors and eliminate or reduce the need for special tools.
- Install appropriate interlocks for blocking access to hazardous locations and provide effective guards against moving parts.
- Develop designs/procedures in such a way that the maintenance error occurrence probability is reduced to a minimum.
- Design for easy accessibility so that parts requiring maintenance are easy and safe to check, replace, service, or remove.
- Incorporate effective fail-safe designs to prevent damage or injury in the event of a failure.
- Eliminate or reduce the need to perform adjustments/maintenance close to hazardous operating parts.
- Incorporate appropriate devices/measures for early detection or prediction of all types of potential failures so that necessary maintenance can be carried out prior to actual failure with a reduced risk of hazards.
- Develop the design in such a way that the probability of maintenance workers being injured by escaping high-pressure gas, electric shock, and so on, is reduced to a minimum.

10.8 MATHEMATICAL MODELS

Over the years, a large number of mathematical models have been developed to perform various types of reliability and availability analysis of engineering systems [17]. Some of these models can also be used to perform maintenance safety-related analysis of engineering systems. One such model is presented below.

This mathematical model represents an engineering system with three states: operating normally, working unsafely (due to maintenance or other problems), and failed. The system is repaired from failed and unsafe working states. The system state space diagram is shown in Figure 10.1. The numerals in boxes and circle denote system states. The Markov method described in Chapter 4 is used to develop equations for system state probabilities and mean time to failure.

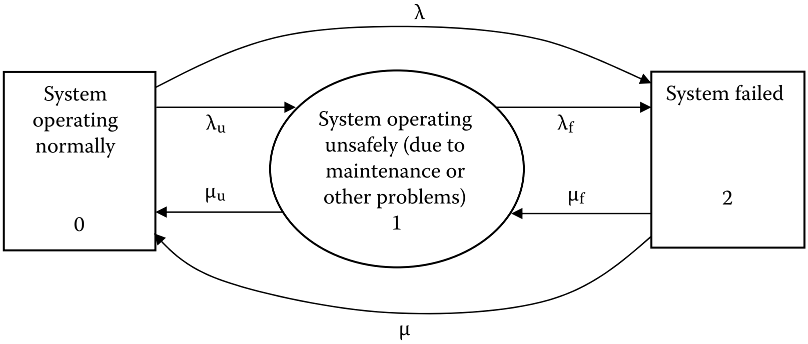

FIGURE 10.1 System state space diagram.

The following assumptions are associated with the model:

- All occurrences are independent of each other.
- System failure and repair rates are constant.
- The repaired system is as good as new.

The following symbols are associated with the diagram:

i is the *i*th state of the system: $i = 0$ (system operating normally), $i = 1$ (system operating unsafely due to maintenance or other problems), $i = 2$ (system failed).
t is time.
$P_i(t)$ is the probability that the system is in state *i* at time *t*; for $i = 0, 1, 2$.
λ is the system constant failure rate.
λ_u is the system constant unsafe degradation rate due to maintenance or other problems.
λ_f is the system constant failure rate from its unsafe operating state 1.
μ is the system constant repair rate from state 2 to state 0.
μ_u is the system constant repair rate from state 1 to state 0.
μ_f is the system constant repair rate from state 2 to state 1.

Using the Markov method, we write down the following equations for the diagram [2, 17]:

$$\frac{dP_0(t)}{dt} + (\lambda_u + \lambda)P_0(t) = \mu_u P_1(t) + \mu P_2(t) \quad (10.1)$$

$$\frac{dP_1(t)}{dt} + (\mu_u + \lambda_f)P_1(t) = \mu_u P_2(t) + \lambda_u P_0(t) \quad (10.2)$$

$$\frac{dP_2(t)}{dt} + (\mu_u + \mu_f)P_2(t) = \lambda_f P_1(t) + \lambda P_0(t) \quad (10.3)$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, and $P_2(0) = 0$.

For a very large t, by solving Equations (10.1)–(10.3), we get the following steady-state probability equations [17]:

$$P_0 = \frac{(\mu + \mu_f)(\mu_u + \lambda_f) - \lambda_f \mu_f}{X} \tag{10.4}$$

where

$$X = (\mu + \mu_f)(\mu_u + \lambda_u + \lambda_f) + \lambda(\mu_u + \lambda_f) + \lambda\, \mu_f + \lambda_u\, \lambda_f - \lambda_f\, \mu_f$$

$$P_1 = \frac{\lambda_u(\mu + \mu_f) + \lambda\mu_f}{X} \tag{10.5}$$

$$P_2 = \frac{\lambda\,\lambda_f + \lambda(\mu_u + \lambda_f)}{X} \tag{10.6}$$

where P_0, P_1, and P_2 are the steady-state probabilities of the system being in states 0, 1, and 2, respectively.

Thus, the steady-state probability of the system operating unsafely due to maintenance or other problems is given by Equation (10.5).

By setting $\mu = \mu_f = 0$ in Equations (10.1)–(10.3) and solving the resulting equations, we get the following equation for the system reliability:

$$\begin{aligned} R_S(t) &= P_0(t) + P_1(t) \\ &= (X_1 + Y_1)e^{x_1 t} + (X_2 + Y_2)e^{x_2 t} \end{aligned} \tag{10.7}$$

where $R_S(t)$ is the system reliability at time t.

$$x_1 = \frac{-L_1 + \sqrt{L_1^2 - 4\,L_2}}{2} \tag{10.8}$$

$$x_2 = \frac{-L_1 - \sqrt{L_1^2 - 4L_2}}{2} \tag{10.9}$$

$$L_1 = \mu_u + \lambda + \lambda_u + \lambda_f \tag{10.10}$$

$$L_2 = \lambda\,\mu_u + \lambda\,\lambda_f + \lambda_u\,\lambda_f \tag{10.11}$$

$$X_1 = \frac{x_1 + \mu_u + \lambda_f}{(x_1 - x_2)} \tag{10.12}$$

$$X_2 = \frac{x_2 + \mu_u + \lambda_f}{(x_2 - x_1)} \tag{10.13}$$

$$Y_1 = \frac{\lambda_u}{(x_1 - x_2)} \tag{10.14}$$

$$Y_2 = \frac{\lambda_u}{(x_2 - x_1)} \tag{10.15}$$

By integrating Equation (10.7) over the time interval [0, ∞], we obtain the following equation for the system mean time to failure with repair [2, 17]:

$$MTTF_{Sr} = \int_0^\infty R_S(t)dt = \left[\frac{(X_1 + Y_1)}{x_1} + \frac{(X_2 + Y_2)}{x_2}\right] \quad (10.16)$$

where $MTTF_{Sr}$ is the system mean time to failure with repair.

Example 10.1

Assume that a repairable engineering system can be either operating normally, operating unsafely due to maintenance or other problems, or failed. Its constant failure/degradation rates from normal operating state to failed state, normal working state to unsafe operating state, and unsafe operating state to failed state are 0.004 failures per hour, 0.002 failures per hour, and 0.001 failures per hour, respectively.

Similarly, the system constant repair rates from the failed state to normal operating state, unsafe operating state to normal operating state, and failed state to unsafe working state are 0.008 repairs per hour, 0.005 repairs per hour, and 0.002 repairs per hour, respectively.

Calculate the steady-state probability of the system being in unsafe operating state due to maintenance or other problems.

By substituting the given data values into Equation (10.5), we get

$$P_1 = \frac{(0.002)(0.008 + 0.002) + (0.004)(0.002)}{X} = 0.25$$

where

$$X = (0.008 + 0.002)(0.005 + 0.002 + 0.001) + 0.004(0.005 + 0.001) + (0.004)(0.002) + (0.002)(0.001) - (0.001)(0.002)$$

Thus, the steady-state probability of the system being in unsafe operating state due to maintenance or other problems is 0.25.

10.9 PROBLEMS

1. Write an essay on safety in engineering maintenance.
2. List at least six facts, figures, and examples directly or indirectly concerned with safety in engineering maintenance.
3. What are the important causes of maintenance safety problems?

4. What are the factors responsible for dubious safety reputation in maintenance activity?
5. Discuss the factors influencing safety behavior and safety culture in maintenance personnel.
6. Discuss at least four good safety-related practices during maintenance work.
7. Discuss maintenance-related safety measures concerning machinery.
8. Write down at least ten maintenance safety-related questions for engineering equipment manufacturers.
9. Prove Equations (10.4)–(10.6) by using Equations (10.1)–(10.3).
10. Assume that an engineering system can be either operating normally, operating unsafely due to maintenance or other problems, or failed. Its constant failure/degradation rates from normal operating state to failed state, normal working state to unsafe operating sate, and unsafe operating state to failed state are 0.003 failures per hour, 0.001 failures per hour, and 0.002 failures per hour, respectively. Similarly, the system constant repair rates from the failed state to normal operating state, unsafe operating state to normal operating state, and failed state to unsafe working state are 0.007 repairs per hour, 0.006 repairs per hour, and 0.001 repairs per hour, respectively. Calculate the steady state probability of the system being in unsafe operating state due to maintenance or other problems.

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