9 Human Error in Power Plant Maintenance

9.1 INTRODUCTION

Maintenance is an essential activity in power plants, and it consumes a significant amount of money spent on power generation. Human error in maintenance has been found to be an important factor in the causation of power generation safety-related incidents [1]. A study of reliability problem-related events concerning electrical/electronic components in nuclear power plants revealed that human errors made by maintenance personnel and technicians exceeded operator errors and that over three-quarters of the errors took place during the testing and maintenance activity [1, 2]. Furthermore, according to Refs. [1, 3], errors made during testing and maintenance caused reactor core melt more easily than did errors during operation.

The cost of maintenance errors, including restoration costs and opportunity costs, is potentially very high, the damage impact on the equipment may decrease its life quite considerably, and serious potential hazards to human lives may result. Because of potentially critical consequences such as these to system function and public safety, the prevention of human errors in maintenance tasks in power generation is receiving increasing attention.

This chapter presents various important aspects of human error in power plant maintenance.

9.2 FACTS AND FIGURES

Some of the facts, figures, and examples directly or indirectly related to human error in power plant maintenance are as follows:

- A study reported that over 20% of all system failures in fossil power plants occur due to human errors and maintenance errors account for about 60% of the annual power loss due to human errors [4].
- A number of studies reported that between 55% and 65% of human performance problems surveyed in power generation were associated with maintenance-related activities [5, 6].
- A study of over 4400 maintenance history records covering the period from 1992 to 1994, concerning a boiling water reactor (BWR) nuclear power plant, reported that around 7.5% of all failure records could be classified as human errors related to maintenance actions [7, 8].
- A study of 199 human errors that occurred in Japanese nuclear power plants from 1965 to 1995 revealed that around 50 of them were related to maintenance activities [9].

- A study of 126 human error-related significant events in 1990, in nuclear power generation, reported that 42% of the problems were linked to maintenance and modification [5].
- On Christmas Day in 1989, two nuclear reactors were shut down due to maintenance error and caused rolling blackouts in the state of Florida [10].
- A blast at the Ford Rouge power plant in Dearborn, Michigan, that killed six workers and injured many others was caused by a maintenance error [11, 12].
- A study of nuclear power plant operating experiences revealed that because of errors in maintenance of some motors in the rod drives, many of the motors ran in a backward direction and withdrew rods, instead of inserting them [13].

9.3 CAUSES OF HUMAN ERROR IN POWER PLANT MAINTENANCE

There are many different causes for the occurrence of human errors in power plant maintenance. On the basis of characteristics obtained from modeling the maintenance task, error causes in power plant maintenance may be classified under four major categories as shown in Figure 9.1 [1].

Design shortcomings in hardware and software include items such as deficiencies in the design of displays and controls, insufficient communication equipment, and wrong or confusing procedures. An example of human ability limitations is the limited capacity of short-term memory in the internal control mechanism.

Some important examples of disturbances of the external environment are the physical conditions such as humidity, ventilation, ambient illumination, and

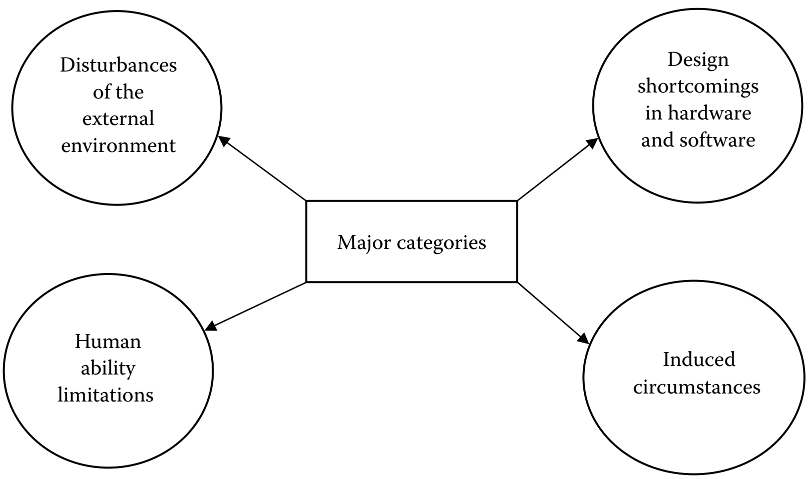

FIGURE 9.1 Major categories of error causes in power plant maintenance.

temperature. Induced circumstances include items such as momentary distractions, improper communications which may result in failures, and emergency conditions.

A study identified the following causal factors, in order of greatest to least frequency of occurrence, for critical incidents and reported events related to maintenance error in power plants [14, 15]:

- Faulty procedures
- Problems in clearing and tagging equipment for maintenance
- Shortcomings in equipment design
- Problems in moving people or equipment
- Poor training
- Poor unit and equipment identification
- Problems in facility design
- Poor work practices
- Adverse environmental factors
- Mistakes by maintenance personnel

"Faulty procedures" are the most frequently appearing causal factor in the mishaps reported. It includes items such as incorrect procedures, incompleteness, lack of specificity, and lack of adherence to a specified procedure. An example of faulty procedures is "due to poor judgment and not following prescribed guidelines properly, a ground was left on a circuit breaker. When the equipment was put back into service, the circuit breaker blew up and caused extensive property damage." In this case, the correct procedure would have required clearing the ground prior to returning the circuit breaker to service.

"Problems in clearing and tagging equipment for maintenance" are the second most frequent causal factor in reported cases where serious accidents/potentially serious accidents could be attributed to a failure/error associated with the equipment clearance process. "Shortcomings in equipment design" are the third most frequent causal factor for accidents/near-accidents revolved about equipment design-related problems. The factor includes items such as the equipment not designed with appropriate mechanical safeguards to prevent the substitution of wrong part for the proper replacement part, equipment installed incorrectly from the outset, parts placed in inaccessible locations, and poorly designed and inherently unreliable components.

"Problems in moving people or equipment" are the fourth most frequent causal factor. These problems basically stem from poor lifting capability or the inability to employ proper vehicular aids in moving heavy units of equipment. "Poor training," "poor unit and equipment identification" and "problems in facility design" are the fifth most frequent causal factors. The factor "poor training" is basically concerned with the unfamiliarity of repair workers with the job or their lack of awareness of the system characteristics and inherent dangers associated with the job at hand. "Poor unit and equipment identification" is the cause of an unexpectedly high number of accidents, and often the problem is confusion between two identical items and sometimes improper identification of potential hazards.

"Problems in facility design" can contribute to accidents. Some examples of these problems are insufficient clearances for repair workers, equipment, or transportation aids in the performance of maintenance activities, and inadequately sized facilities causing an overly dense packaging of equipment systems and preventing effective performance of repair or inspection tasks.

"Poor work practices" are the sixth most frequent causal factor. Some examples of poor work practices are not waiting for operators to complete the switching and tagging tasks essential to disable the systems requiring attention and not taking the time to erect a scaffold so that an item in midair can be accessed safely.

"Adverse environmental factors" and "mistakes by maintenance personnel" are the seventh (or the least) frequent causal factors. The "adverse environmental factors" include items such as the need to wear protective garments and devices in threatening environments that, in turn, restrict a person's movement capabilities and visual field, and the encouragement of haste by the need to minimize stay time in, say, radioactive environments. "Mistakes by maintenance personnel" are a small fraction of those errors that would be difficult to anticipate and "design-out" of power generation plants.

Additional information on all of the above causal factors is available in Ref. [14].

9.4 MAINTENANCE TASKS MOST SUSCEPTIBLE TO HUMAN ERROR IN POWER GENERATION

In the 1990s the Central Research Institute of Electric Power Industry (CRIEPI) in Japan and the Electric Power Research Institute in the United States conducted a joint study to identify critical maintenance tasks and to develop, implement, and evaluate interventions that have high potential to reduce the occurrence of human errors or increasing maintenance productivity in nuclear power plants. As the result of this study, five maintenance tasks most susceptible to the occurrence of human errors, as shown in Figure 9.2, were identified [16]. It simply means that careful attention is necessary in performing such tasks to minimize or eliminate the occurrence of human errors.

9.5 METHODS FOR PERFORMING MAINTENANCE ERROR ANALYSIS IN POWER GENERATION

Over the years, many methods or models have been developed that can be used to perform maintenance error analysis in power generation. Three such methods/models are presented below.

9.5.1 Fault Tree Analysis

This is a widely used method in the industrial sector to perform various types of reliability-related analysis [17, 18]. The method is described in detail in Chapter 4. Its application to the performance of maintenance error analysis in the area of power generation is demonstrated through the following example:

Example 9.1

Assume that a piece of power plant equipment can fail due to a maintenance error caused by four factors: poor work environment, carelessness, poor equipment design,

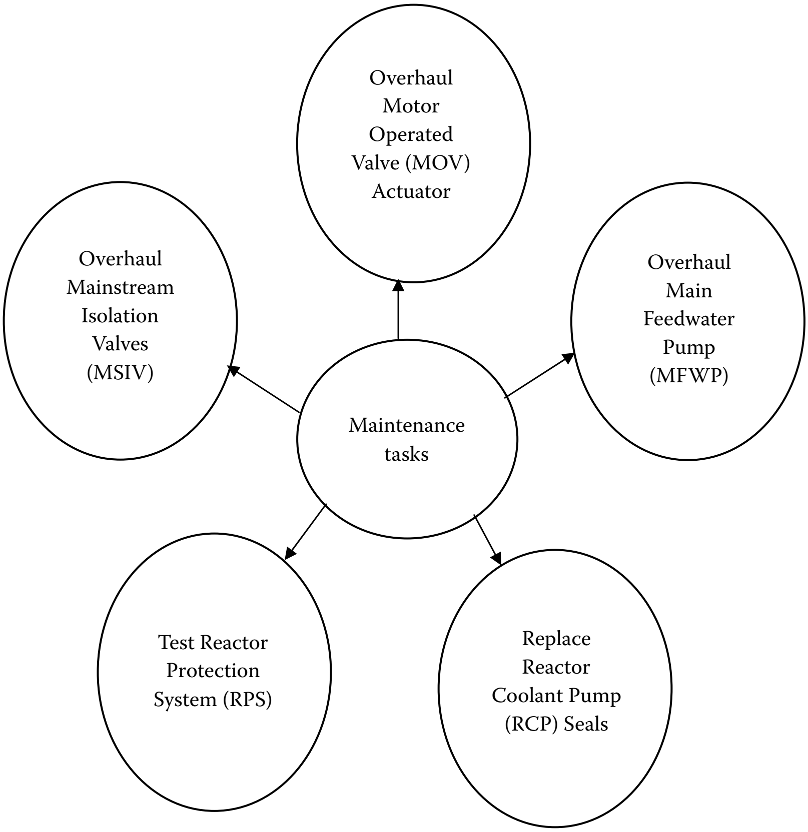

FIGURE 9.2 Maintenance tasks most susceptible to human errors.

and use of deficient maintenance manuals. Two major factors for poor work environment are inadequate lighting or distractions. Similarly, three factors for poor equipment design are oversight, misinterpretation of design specification, or no formal consideration to maintenance error occurrence in design specification. Finally, two factors for carelessness are poor training or time constraints.

Develop a fault tree for the top event "Power plant equipment failure due to a maintenance error" by using fault tree symbols given in Chapter 4.

A fault tree for the example is shown in Figure 9.3.

Example 9.2

Assume that the probability of occurrence of events E_1, E_2, $E_3, \ldots,$ E_8 shown in Figure 9.3 is 0.01. For independent events, calculate the probability of occurrence of the top event T (i.e., power plant equipment failure due to a maintenance error), and intermediate events I_1, (i.e., carelessness), I_2 (i.e., poor equipment design) and I_3 (i.e., poor work environment).

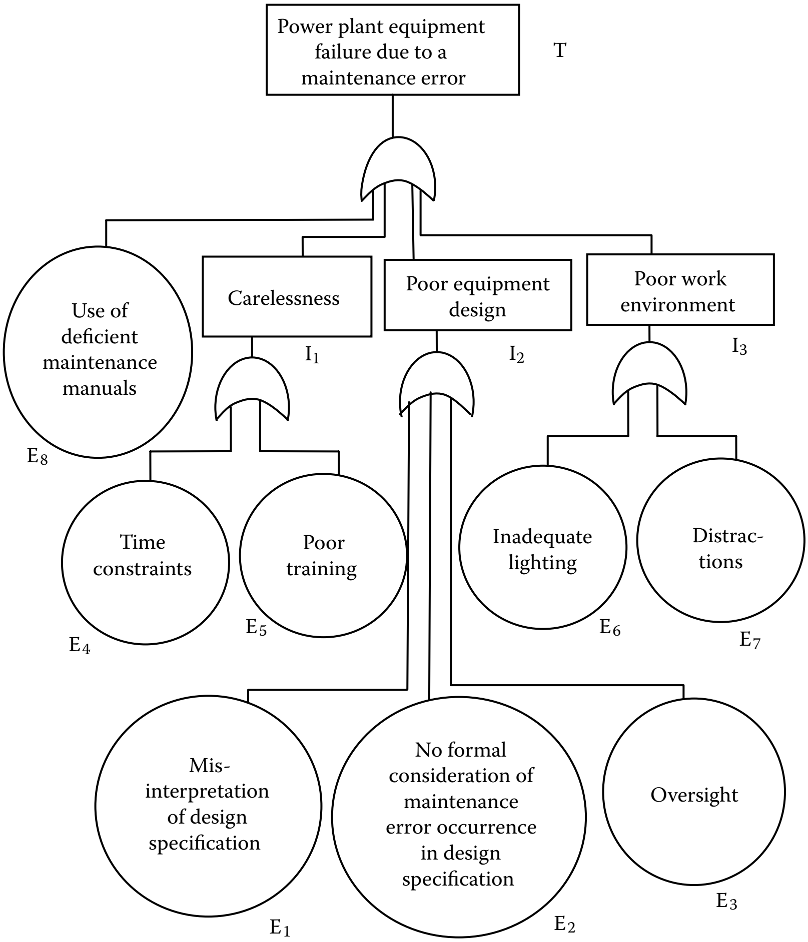

FIGURE 9.3 Fault tree for Example 9.1.

Using Chapter 4, Refs. [17, 18], and the given data, we obtain the values of I_1, I_2, I_3, and T as follows:

The probability of occurrence of event I_1 is given by

$$\begin{aligned} P(I_1) &= P(E_4) + P(E_5) - P(E_4)P(E_5) \\ &= 0.01 + 0.01 - (0.01)(0.01) \\ &= 0.0199 \end{aligned} \tag{9.1}$$

where $P(I_1)$, $P(E_4)$, and $P(E_5)$ are the probabilities of occurrence of events I_1, E_4, and E_5, respectively.

The probability of occurrence of event I_2 is

$$\begin{aligned} P(I_2) &= 1-\{1-P(E_1)\}\{1-P(E_2)\}\{1-P(E_3)\} \\ &= 1-\{1-0.01\}\{1-0.01\}\{1-0.01\} \\ &= 0.0297 \end{aligned} \tag{9.2}$$

where $P(I_2)$, $P(E_1)$, $P(E_2)$, and $P(E_3)$ are the probabilities of occurrence of events I_2, E_1, E_2, and E_3, respectively.

The probability of occurrence of event I_3 is given by

$$\begin{aligned} P(I_3) &= P(E_6)+P(E_7)-P(E_6)P(E_7) \\ &= 0.01+0.01-(0.01)(0.01) \\ &= 0.0199 \end{aligned} \tag{9.3}$$

where $P(I_3)$, $P(E_6)$, and $P(E_7)$ are the probabilities of occurrence of events I_3, E_6, and E_7, respectively.

By using the above calculated and the specified values, Chapter 4, and Refs. [17, 18] we get

$$\begin{aligned} P(T) &= 1-\{1-P(E_8)\}\{1-P(I_1)\}\{1-P(I_2)\}\{1-P(I_3)\} \\ &= 1-(1-0.01)(1-0.0199)(1-0.0297)(1-0.0199) \\ &= 0.0772 \end{aligned} \tag{9.4}$$

Thus, the probabilities of occurrence of events T, I_1, I_2, and I_3 are 0.0772, 0.0199, 0.0297, and 0.0199, respectively.

9.5.2 Markov Method

This is a widely used method to perform reliability analysis of repairable engineering systems, and it can be used to perform maintenance error analysis in power plants. The method is described in Chapter 4. Its application to perform maintenance error analysis in the area of power generation is demonstrated through the mathematical model presented below.

This mathematical model represents a power plant system that might fail due to a maintenance error or non-maintenance error failures. The system state space diagram is shown in Figure 9.4 [19]. Numerals in boxes denote system states. The following assumptions are associated with the model:

- The system maintenance error and non-maintenance error failure rates are constant.
- The failed system is repaired and the repaired system is as good as new.
- Failed system repair rates are constant.

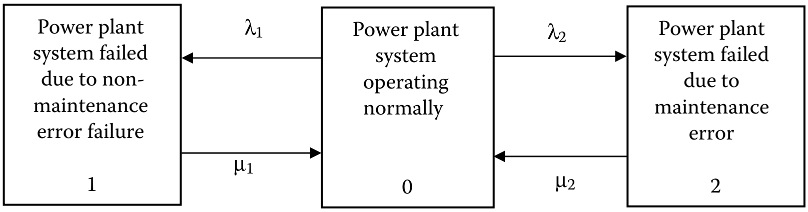

FIGURE 9.4 System state space diagram.

The following symbols are associated with the model:

i is the system state i; for $i = 0$ (power plant system operating normally), $i = 1$ (power plant system failed due to non-maintenance error failure), $i = 2$ (power plant system failed due to maintenance error).

$P_i(t)$ is the probability that the power plant system is in state i at time t; for $i = 0, 1, 2$.

λ_1 is the power plant system constant non-maintenance error failure rate.

μ_1 is the power plant system constant repair rate from state 1 to state 0.

λ_2 is the power plant system constant maintenance error rate.

μ_2 is the power plant system constant repair rate from state 2 to state 0.

By applying the Markov method described in Chapter 4, we write down the following equations for the diagram:

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2)P_0(t) = \mu_1 P_1(t) + \mu_2 P_2(t) \tag{9.5}$$

$$\frac{dP_1(t)}{dt} + \mu_1 P_1(t) = \lambda_1 P_0(t) \tag{9.6}$$

$$\frac{dP_2(t)}{dt} + \mu_2 P_2(t) = \lambda_2 P_0(t) \tag{9.7}$$

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

By solving Equations (9.5)–(9.7), we get

$$P_0(t) = \frac{\mu_1\mu_2}{x_1 x_2} + \left[\frac{(x_1 + \mu_2)(x_2 + \mu_1)}{x_1(x_1 - x_2)}\right]e^{x_1 t} - \left[\frac{(x_2 + \mu_2)(x_2 + \mu_1)}{x_2(x_1 - x_2)}\right]e^{x_2 t} \tag{9.8}$$

where

$$x_1, x_2 = \frac{-\beta \pm \sqrt{\beta^2 - 4(\mu_2\mu_1 + \lambda_2\mu_t\lambda_1\mu_1)}}{2} \tag{9.9}$$

$$\beta = \mu_2 + \mu_1 + \lambda_1 + \lambda_2 \tag{9.10}$$

$$x_1 x_2 = \mu_1 \mu_2 + \lambda_2 \mu_1 + \lambda_1 \mu_2 \tag{9.11}$$

$$x_1 + x_2 = -(\mu_2 + \mu_1 + \lambda_2 + \lambda_1) \tag{9.12}$$

$$P_1(t) = \frac{\lambda_2 \mu_1}{x_1 x_2} + \left[\frac{\lambda_1 x_1 + \lambda_1 \mu_2}{x_1(x_1 - x_2)}\right] e^{x_1 t} - \left[\frac{(\mu_2 + x_2)\lambda_2}{x_2(x_1 - x_2)}\right] e^{x_2 t} \tag{9.13}$$

$$P_2(t) = \frac{\lambda_1 \mu_2}{x_1 x_2} + \left[\frac{\lambda_1 x_1 + \lambda_1 \mu_2}{x_1(x_1 - x_2)}\right] e^{x_1 t} - \left[\frac{(\mu_2 + x_2)\lambda_1}{x_2(x_1 - x_2)}\right] e^{x_2 t} \tag{9.14}$$

As t becomes very large, we get the following steady-state probability equations from Equations (9.8), (9.13), and (9.14), respectively:

$$P_0 = \frac{\mu_1 \mu_2}{x_1 x_2} \tag{9.15}$$

$$P_1 = \frac{\lambda_2 \mu_1}{x_1 x_2} \tag{9.16}$$

and

$$P_1 = \frac{\lambda_1 \mu_2}{x_1 x_2} \tag{9.17}$$

where P_0, P_1, and P_2 are the steady-state probabilities of the power plant system being in states 0, 1, and 2, respectively. It is to be noted that Equation (9.15) is also known as the system steady-state availability.

Example 9.3

Assume that we have the following data values for a power plant system:

$\lambda_1 = 0.006$ failures per hour

$\lambda_2 = 0.001$ errors per hour

$\mu_1 = 0.04$ repairs per hour

$\mu_2 = 0.02$ repairs per hour

Calculate the steady-state probability of the system failing due to maintenance error.

By substituting the specified data values into Equation (9.17), we get

$$\begin{aligned} P_2 &= \frac{\lambda_1 \mu_2}{x_1 x_2} = \frac{\lambda_1 \mu_2}{(\mu_1 \mu_2 + \lambda_2 \mu_1 + \lambda_1 \mu_2)} \\ &= \frac{(0.006)(0.02)}{[(0.04)(0.02) + (0.001)(0.04) + (0.006)(0.02)]} \\ &= 0.1259 \end{aligned}$$

Thus, the steady-state probability of the power plant system failing due to maintenance error is 0.1259.

9.5.3 Maintenance Personnel Performance Simulation (MAPPS) Model

This is a computerized, stochastic, task-oriented human behavioral model developed by the Oak Ridge National Laboratory, for providing estimates of nuclear power plant (NPP) maintenance manpower performance measures [20]. Its development was sponsored by the United States Nuclear Regulatory Commission (NRC), and the primary objective for its development was the need for and lack of a human reliability-related data bank pertaining to NPP maintenance activities, for use in performing probabilistic risk assessment (PRA) studies.

The measures of performance estimated by MAPPS include the probability of successfully completing the task of interest, the task duration time, probability of an undetected error, maintenance team stress profiles during task execution, and identification of the most-and least-likely error-prone subelements. Needless to say, the MAPPS model is a powerful tool for estimating important maintenance parameters and its flexibility allows it to be useful for various applications dealing with NPP maintenance activity.

Additional information on the MAPPS model is available in Ref. [20].

9.6 STEPS FOR IMPROVING MAINTENANCE PROCEDURES IN POWER GENERATION AND USEFUL GUIDELINES FOR HUMAN ERROR REDUCTION AND PREVENTION IN POWER GENERATION MAINTENANCE

Past experiences indicate that improving maintenance procedures in power generation can help to reduce performance errors along with a corresponding increase in unit reliability. In general, the upgrade of a maintenance procedure can be accomplished by following the steps listed below [21].

- **Step 1:** This is concerned with selecting a procedure to be upgraded by considering factors such as user inputs and relative importance of the procedure.
- **Step 2:** This is concerned with reviewing the procedure with respect to items such as device nomenclature, tolerances, required test equipment, limits, step sequence, prerequisites, and precautions.
- **Step 3:** This is concerned with reviewing the procedure for agreement with the procedure development guidelines.
- **Step 4:** This is concerned with the preliminary validation of the procedure to determine its usability.
- **Step 5:** This is concerned with rewriting the procedure by taking into consideration the results of Steps 2, 3, and 4.
- **Step 6:** This is concerned with reviewing the revised procedure with respect to technical accuracy and agreement with the "Procedure Development Guide."

- **Step 7:** This is concerned with evaluating the revised procedure with respect to its usability by those responsible for performing it.
- **Step 8:** This is concerned with the approval of the upgraded procedure by appropriate supervisory and management personnel.

An upgraded maintenance procedure can substantially contribute to many areas including fewer human performance errors, identification of needed training, identification of desirable plant modifications, higher level of employee morale, and better unit reliability [21].

Additional information on improving maintenance procedures in power plants is available in Ref. [21].

Over the years, various guidelines have been proposed to reduce and prevent the occurrence of human error in power generation maintenance. Four of these guidelines are as follows [1]:

- **Revise training programs for all concerned maintenance personnel.** It basically means that training programs for maintenance personnel should be revised in accordance with the characteristics and frequency of occurrence of each extrinsic cause.
- **Ameliorate design deficiencies.** As deficiencies in design can reduce attention to the tasks and may even induce human error, this guideline calls for overcoming deficiencies in areas such as labeling, coding, plant layout, and work environment.
- **Carry out administrative policies more thoroughly.** It basically means motivating maintenance personnel appropriately to comply with prescribed quality control procedures.
- **Develop appropriate work safety checklists for maintenance personnel.** It means that maintenance personnel should be provided with work safety checklists, which can be used to determine the possibility of human error occurrence and the factors that may affect their actions prior to or after the performance of maintenance tasks.

Additional information on the above four guidelines is available in Ref. [1].

9.7 PROBLEMS

1. Write an essay on human error in power plant maintenance.
2. Discuss at least four facts and figures concerning human error in power plant maintenance.
3. What are the major causes of error in power plant maintenance?
4. Discuss power plant maintenance tasks that are most susceptible to human error.
5. Prove Equations (9.8), (9.13), and (9.14) by using Equations (9.5)–(9.7).
6. Prove that the sum of Equations (9.8), (9.13), and (9.14) is equal to unity.
7. Describe the maintenance personnel performance simulation (MAPPS) model.

8. What are the steps that can be used for improving maintenance procedures in power generation?
9. Discuss at least three useful guidelines for human error reduction and prevention in power plant maintenance.
10. List ten causal factors in order of greatest to least frequency of occurrence, for critical incidents and reported events directly or indirectly related to maintenance error in power plants.

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