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Human Factors and Human Error in Nuclear Power Plant Maintenance

10.1 Introduction

In nuclear power plant maintenance, human factors play an important role because improving the maintainability design of power plant facilities, equipment, and systems with regard to human factors helps to directly or indirectly increase plant availability, safety, and productivity. Interest in human factor-related issues in the nuclear power industrial sector is relatively new in comparison to the aerospace industrial sector. Its history goes back to the 1970s when the WASH-1400 Reactor Safety Study criticized the deviation of controls’ and displays’ design in the commercial nuclear power plants of the United States from the human factors engineering-related set standards [1–3].

A number of studies performed over the years clearly indicate that the occurrence of human error in maintenance is an important factor in nuclear power plant safety-related incidents [4,5]. For example, a study concerning nuclear power plant operating experiences reported that because of human errors in the maintenance of some motors in the rod drives, a number of motors ran backward and withdrew rods instead of inserting them [5]. Needless to say, over the years, the occurrence of many human factors’ shortcomings-related events and human errors in nuclear power plants has led to an increased attention to human factors and human errors in nuclear power plant maintenance.

This chapter presents various important aspects of human factors and human errors in the area of nuclear power plant maintenance.

10.2 Study of Human Factors in Power Plant Maintenance

A study concerning the maintenance of five nuclear and four fossil-fuel power plants with respect to human factors reported various types of directly or indirectly human factor-related problems [6,7]. The study was quite wide-ranging...
in scope, extending to an examination of items such as environmental factors, organizational factors, designs, tools, spares, facilities, and procedures.

The findings of the study were grouped under equipment maintainability; maintenance, information, procedures, and manuals; facility design factors; anthropometrics and human strength; environmental factors; communications; personal safety; movement of humans and machines; labeling and coding; maintenance stores, supplies, and tools; maintenance errors and accidents; preventive maintenance and malfunction diagnosis; equipment protection; productivity and organizational interfaces; job practices; and selection and training. The first seven of these groups are described below [6,7].

The equipment maintainability’s most common problem is the placement of equipment parts in locations that are inaccessible from a normal work position. The maintenance information, procedures, and manuals’ main problem is inadequate manuals and poorly written procedures. The facility design factor problems include poor temperature–ventilation control, high noise levels, insufficient storage space to satisfy maintenance needs effectively, and inadequate facilities to store contaminated equipment.

An example of anthropometrics and human strength problems is the lack of easy access to equipment requiring maintenance. Two examples of the problems belonging to environmental factors are heat stress and a high variability of illumination. The communications problems include inadequate capacity of the existing communications system for satisfying the volume of communications traffic needed throughout the plant, particularly during outages, the protective clothing worn by maintenance personnel while working in radioactive environment causes serious impediments to effective communications and insufficient communication coverage throughout the power plant. Finally, some examples of personnel safety problems are steam burns, heat prostration, radiation exposure, and chemical burns.

Additional information on all of the above groups of findings is available in References 6 and 7.

10.3 Elements Relating to Human Performance That Can Contribute to an Effective Maintenance Program in Nuclear Power Plants

There are many elements relating to human performance that can directly or indirectly contribute to an effective maintenance program in nuclear power plants. Six of these elements are as follows [3,8]:

- **Element 1**: Good planning
- **Element 2**: Design for maintainability
10.4 Useful Human Factors Methods to Assess and Improve Nuclear Power Plant Maintainability

There are many human factors methods that can be used to assess and improve nuclear power plant maintainability. Five of these methods are described below, separately [6,9].

10.4.1 Structured Interviews

This is one of the most effective methods used for collecting valuable data concerning maintainability in the shortest possible time. The method assumes that personnel such as repair persons, technicians, and their supervisors close to maintainability-related problems generally provide the most meaningful insights into the difficulties involved in carrying out their job the best possible way. In a structured interview, a fixed set of questions such as presented below are asked [6,9,10].

- Are appropriate lay down areas and workbenches provided?
- Is your workshop facility arranged in such a way so that it allows efficient and safe performance of all maintenance-related activities?
- How would you describe the environment in your workshop facility with regard to factors such as noise, illumination, and ventilation?
- Is our workshop facility sized properly for accommodating effectively all the personnel in your organization?
- How well is your workshop facility integrated into the overall/total plant design?

After analyzing all the collected data, necessary recommendations for improvements are made. Additional information on this method is available in References 6 and 9.
10.4.2 Task Analysis

This is a systematic approach used for assessing the equipment maintainer’s requirements for successfully working with hardware to accomplish a specified task. The involved analyst oversees and records each task element and start and completion times in addition to making observations that are impediments to effective maintainability.

The observations are grouped under 16 classifications. These are equipment damage potential, availability of appropriate maintenance information (i.e., procedures, manuals, and schematics), environmental factors, equipment maintainability design features, facility design features, decision-making factors, access factors, workshop adequacy, personal hazards, lifting or movement aids, maintenance crew interactions, communication, tools and job aids, spare parts retrieval, supervisor-subordinate relationships, and training needs [6].

Additional information on this method is available in References 6 and 9.

10.4.3 Surveys

This method is used when the results obtained through the application of methods such as structured interviews and task analysis indicate a need for more detailed examination of certain maintainability-related factors. Two examples of such scenario are presented below [9,10]:

- **Example 1:** Most maintenance personnel have expressed concerns in the area of communications. Under such situations, it might be quite helpful to carry out a survey or test of message intelligibility between important communication links within the power plant facility.
- **Example 2:** Inadequate illumination is, directly or indirectly, proving to be a problem in the course of analyzing one or more certain tasks. In such situations, it might be quite helpful to carry out a power plant–wide illumination survey of all maintenance worksites.

Additional information on this method is available in Reference 9.

10.4.4 Potential Accident/Damage Analysis

This is a quite useful structured approach for assessing the accident, damage, or potential error inherent in a stated task. To determine the potential for mishaps’ occurrence in the performance of a maintenance job, the starting point is to establish an appropriate mechanism that clearly describes the job under consideration in detail. Subsequently for each and every task element, the interviewer of the interviewee (e.g., repair person) asks the following question:

- Is there a low, medium, or high potential for the occurrence of an error/an accident/damage to system/equipment in carrying out, say, step xyz?
After analyzing all the collected data, appropriate changes to items such as equipment, facility, and procedures are recommended. Additional information on this method is available in References 6 and 9.

### 10.4.5 Critical Incident Technique

Past experiences over the years clearly indicate that maintenance errors', accidents', or near mishaps' history can provide useful information concerning needed maintainability-related improvements. In this regard, the critical incident technique is considered a very good tool for examining such case histories from the standpoint of human factors. The application of this tool/technique calls for making appropriate arrangements to meet individually with members of the maintenance organization. To each individual, the following three questions are asked:

- Give one example of a plant system or unit of equipment that is quite well “human engineered” or quite straightforward to maintain, and describe the unit/system by emphasizing the features that make it good from the maintainer's perspective.
- Based on your personal experience, give one example of a maintenance error, accident, or near mishap with serious or potentially serious consequences. Furthermore, describe the specifics of the case and indicate the possible ways the situation could have been averted.
- Give one example of a plant system or unit of equipment that is not properly “human engineered” or from the maintenance person's perspective is quite poorly designed and which has resulted in or could lead to a safety hazard, damage to equipment, or an error.

After analyzing all the collected data, necessary changes for improvements are recommended. Additional information on this technique is available in References 6 and 9.

### 10.5 Nuclear Power Plant Maintenance Error-Related Facts, Figures, and Examples

Some of the facts, figures, and examples that are directly or indirectly concerned with human error in nuclear power plant maintenance are as follows:

- In 1990, a study of 126 human error-related significant events in the area of nuclear power generation reported that approximately 42% of the problems were linked to maintenance and modification [11].
As per References 12 and 13, a study of over 4400 maintenance history records covering the period from 1992–1994 concerning a boiling water reactor (BWR) nuclear power plant revealed that approximately 7.5% of all failure records could be categorized as human errors related to maintenance activities.

In 1989 on Christmas Day in the state of Florida, two nuclear reactors were shut down due to maintenance error and caused rolling blackouts [14].

As per Reference 5, a study of nuclear power plant operating-related experiences revealed that due to errors in maintenance of some motors in the rod drives, many of these motors ran in a backward direction and withdrew rods instead of inserting them.

As per Reference 15, in South Korean nuclear power plants, about 25% of sudden shutdowns were due to human errors, out of which over 80% were human errors resulting from normal testing and maintenance-related tasks.

As per Reference 16, a study of 199 human errors that took place in Japanese nuclear power plants during the period from 1965–1995 reported that approximately 50 of them were concerned with maintenance activities.

10.6 Causes of Human Error in Nuclear Power Plant Maintenance and Maintenance Tasks Most Susceptible to Human Error in Nuclear Power Plants

There are many causes for the human error occurrence in nuclear power plant maintenance activities. On the basis of characteristics obtained from modelling the maintenance-related task, error causes in nuclear power plant maintenance may be grouped under the following four classifications [4]:

- **Design-related shortcomings in software and hardware.** These shortcomings include items such as confusing or wrong procedures, insufficient communication equipment, and deficiencies in the design of displays and controls.

- **Human ability-related limitations.** An example of these limitations is the limited capacity of short-term memory in the internal control mechanism.

- **Induced circumstances.** These circumstances include items such as emergency conditions; improper communications, which may lead to failures; and momentary distractions.
Disturbances of the external environment. Some important examples of these disturbances are the physical conditions such as humidity, temperature, ambient illumination, and ventilation.

The Electric Power Research Institute (EPRI) in the United States and the Central Research Institute of Electric Power Industry (CRIEPI) in Japan carried out a joint study in the 1990s to identify critical maintenance-related tasks and to develop, implement, and evaluate interventions that have a very high potential for reducing the occurrence of human errors or increasing maintenance productivity in nuclear power stations. As the result of this joint study, five maintenance-related tasks most susceptible to the human error occurrence, as shown in Figure 10.1, were highlighted [17]. Additional information on these five maintenance-related tasks is available in Reference 17.

10.7 Digital Plant Protection Systems Maintenance

Task-Related Human Errors

Nowadays, in order to take advantage of digital technology, the analog test reactor protection systems are being replaced by the digital plant protection systems. The scope of human error occurrence incidents in digital plant protection systems during the performance of a maintenance-related task is quite high, ranging from missing an important step of work procedure to
intentional deviation of work procedure from the proper work procedure in order to save time or accomplishing the task easily in an uncomfortable environment.

The types of human errors that can occur in digital plant protection systems maintenance tasks are as follows [18,19]:

- **Resetting error.** This type of error occurs from a failure to reset bistable process parameters after completion of a test.
- **Calibration error.** This type of error is associated with an incorrect setting of trip limits or references.
- **Installation/repair error.** This type of error occurs when faulty parts are replaced or repaired during the refueling maintenance process as a corrective or preventive measure.
- **Quality error.** This type of error occurs basically due to carelessness and limited space for work or transport. Two typical examples of quality error are deficient welding/soldering joints or insulation and too little or too much tightening of screws.
- **Bypass error.** This type of error occurs whenever a channel is bypassed to conduct tests in that very channel.
- **Restoration error.** This type of error occurs from an oversight to restore the system after completion of maintenance or a test.

10.8 Useful Guidelines for Human Error Reduction and Prevention in Nuclear Power Plant Maintenance

Over the years, various useful guidelines have been proposed for reducing and preventing human error occurrence in nuclear power plant maintenance. Four of these guidelines are presented below [4,10]:

- **Guideline 1: Ameliorate design-related deficiencies.** This guideline calls for overcoming deficiencies in areas such as plant layout, labeling, work environment, and coding.
- **Guideline 2: Develop proper work safety checklists for maintenance personnel.** This guideline calls for providing maintenance personnel safety checklists that can be used to determine the possibility of human error occurrence as well as the factors that may affect their actions before or after the performance of maintenance tasks.
- **Guideline 3: Revise training programs for all involved maintenance personnel.** This guideline calls for training programs for all
involved maintenance personnel to be revised in accordance with the characteristics and frequency of occurrence of each extrinsic cause.

- **Guideline 4: Carry out administrative policies more thoroughly.** This guideline calls for motivating maintenance personnel appropriately to comply with prescribed quality control-related procedures.

Additional information on the above guidelines is available in Reference 4.

### 10.9 Methods for Performing Maintenance Error Analysis in Nuclear Power Plants

There are many methods/models that can be used for performing human error analysis in the area of nuclear power plant maintenance. Three of these methods/models are presented below.

#### 10.9.1 Markov Method

This method is widely used for performing probability analysis of repairable engineering systems, and it can also be used for performing human error analysis in the area of nuclear power plant maintenance. The method is described in Chapter 4, and its application to perform maintenance error analysis in nuclear power plants is demonstrated through the mathematical model presented below.

This mathematical model represents a repairable nuclear power plant system that may fail due to a maintenance error or nonmaintenance error failures. The nuclear power plant system state space diagram is shown in Figure 10.2 [10,20]. Numerals in the circle and boxes denote system states. The following assumptions are associated with the mathematical model:

- The nuclear power plant system maintenance error and nonmaintenance error failure rates are constant.

![Nuclear power plant system state space diagram](image)

**FIGURE 10.2**
Nuclear power plant system state space diagram.
The failed nuclear power plant system repair rates are constant.
The repaired nuclear power plant system is as good as new.

The following symbols are associated with the mathematical model:

\( j \) is the nuclear power plant system state \( j \); for \( j = 0 \) (nuclear power plant system operating normally), \( j = 1 \) (nuclear power plant system failed due to nonmaintenance error failure), \( j = 2 \) (nuclear power plant system failed due to maintenance error).

\( P_j(t) \) is the probability that the nuclear power plant system is in state \( j \) at time \( t \) for \( j = 0, 1, 2 \).

\( \lambda_1 \) is the nuclear power plant system constant nonmaintenance error failure rate.

\( \lambda_2 \) is the nuclear power plant system constant maintenance error rate.

\( \theta_1 \) is the nuclear power plant system constant repair rate from state 1 to state 0.

\( \theta_2 \) is the nuclear power plant system constant repair rate from state 2 to state 0.

By using the Markov method described in Chapter 4, we write the following equations for Figure 10.2 state space diagram:

\[
\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2)P_0(t) = \theta_1 P_0(t) + \theta_2 P_2(t) \tag{10.1}
\]

\[
\frac{dP_1(t)}{dt} + \theta_1 P_1(t) = \lambda_1 P_0(t) \tag{10.2}
\]

\[
\frac{dP_2(t)}{dt} + \theta_2 P_2(t) = \lambda_2 P_0(t) \tag{10.3}
\]

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

By solving Equations 10.1 through 10.3, we get

\[
P_0(t) = \frac{\theta_1 \theta_2}{y_1 y_2} \left[ \frac{(y_1 + \theta_2)(y_2 + \theta_1)}{y_1(y_1 - y_2)} \right] e^{y_1 t} - \left[ \frac{(y_2 + \theta_2)(y_2 + \theta_1)}{y_2(y_1 - y_2)} \right] e^{y_2 t} \tag{10.4}
\]

where

\[
y_1, y_2 = \frac{B \pm [B^2 - 4(\theta_1 \theta_2 + \lambda_2 \theta_1 + \lambda_1 \theta_1)]^{1/2}}{2} \tag{10.5}
\]
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\[ B = \theta_1 + \theta_2 + \lambda_1 + \lambda_2 \] (10.6)

\[ y_1y_2 = \theta_1\theta_2 + \lambda_2\theta_1 + \lambda_1\theta_2 \] (10.7)

\[ y_1 + y_2 = -(\theta_1 + \theta_2 + \lambda_1 + \lambda_2) \] (10.8)

\[
P_1(t) = \frac{\lambda_2\theta_1}{y_1y_2} + \left[ \frac{\lambda_1y_1 + \lambda_2\theta_2}{y_1(y_1 - y_2)} \right] e^{\nu t} - \left[ \frac{(\theta_2 + y_2)\lambda_2}{y_2(y_1 - y_2)} \right] e^{\nu t}
\] (10.9)

\[
P_2(t) = \frac{\lambda_2\theta_1}{y_1y_2} + \left[ \frac{\lambda_1y_1 + \lambda_2\theta_2}{y_1(y_1 - y_2)} \right] e^{\nu t} - \left[ \frac{(\theta_2 + y_2)\lambda_1}{y_2(y_1 - y_2)} \right] e^{\nu t}
\] (10.10)

As \( t \) becomes very large, we get the following steady-state probability equations from Equations 10.4, 10.9, and 10.10, respectively:

\[
P_0 = \frac{\theta_1\theta_2}{y_1y_2}
\] (10.11)

\[
P_1 = \frac{\lambda_2\theta_1}{y_1y_2}
\] (10.12)

\[
P_2 = \frac{\lambda_2\theta_1}{y_1y_2}
\] (10.13)

where

\( P_0, P_1, P_2 \) are the steady-state probabilities of the nuclear power plant system being in states 0, 1, and 2, respectively.

It should be noted that Equation 10.11 is also known as the system steady-state availability. In this case, it is the steady-state availability of the nuclear power plant system.

**EXAMPLE 10.1**

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

\[ \lambda_1 = 0.0008 \text{ failures per hour} \]
\[ \theta_1 = 0.06 \text{ repairs per hour} \]
\[ \lambda_2 = 0.0001 \text{ errors per hour} \]
\[ \theta_2 = 0.04 \text{ repairs per hour} \]
Calculate the nuclear power plant system steady-state availability and the steady-state probability of failing due to maintenance error. By substituting the given data values into Equation 10.11, we get

\[
P_0 = \frac{\theta_1 \theta_2}{y_1 y_2} = \frac{\theta_1 \theta_2}{\theta_1 \theta_2 + \lambda_2 \theta_1 + \lambda_1 \theta_2} = \frac{(0.06)(0.04)}{(0.06)(0.04) + (0.0001)(0.06) + (0.0008)(0.04)} = 0.9844
\]

Similarly, by inserting the specified data values into Equation 10.13, we get

\[
P_1 = \frac{\lambda_1 \theta_2}{y_1 y_2} = \frac{\lambda_1 \theta_2}{\theta_1 \theta_2 + \lambda_2 \theta_1 + \lambda_1 \theta_2} = \frac{(0.0008)(0.04)}{(0.06)(0.04) + (0.0001)(0.06) + (0.0008)(0.04)} = 0.0131
\]

Thus, the nuclear power plant system steady-state availability and the steady-state probability of failing due to maintenance error are 0.9844 and 0.0131, respectively.

10.9.2 Fault Tree Analysis

This method is often used to perform various types of reliability-related analysis in the industrial sector [21, 22]. The method is described in detail in Chapter 4. Its application to perform human error analysis in the area of nuclear power plant maintenance is demonstrated through the example presented below.

EXAMPLE 10.2

Assume that a system used in a nuclear power plant can fail due to a maintenance error caused by any of these four factors: poor system design, carelessness, poor work environment, and use of deficient maintenance manuals. Two major factors for carelessness are time constraints or poor training. Similarly, two factors for a poor work environment are distractions or poor lighting.

Develop a fault tree for the top event “nuclear power plant system 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 10.3.

EXAMPLE 10.3

Assume that the occurrence probability of events \( Y_1, Y_2, Y_3, Y_4, Y_5 \) and \( Y_6 \) shown in Figure 10.3 is 0.04. For independent events, calculate the
occurrence probability of the top event $T$ (i.e., nuclear power plant system failure due to a maintenance error), and intermediate events $I_1$ (i.e., carelessness), and $I_2$ (i.e., poor work environment). Also, redraw Figure 10.3 fault tree with given and calculated values.

By using Chapter 4 and the given data values, we obtain the values of $I_1$, $I_2$ and $T$ as follows:

The probability of occurrence of event $I_1$ is given by

$$P(I_1) = P(Y_2) + P(Y_3) - P(Y_2)P(Y_3)$$
$$= 0.04 + 0.04 - (0.04)(0.04)$$
$$= 0.0784$$

where

$P(I_1)$, $P(Y_2)$, and $P(Y_3)$ are the occurrence probabilities of events $I_1$, $Y_2$, and $Y_3$, respectively.

The probability of occurrence of event $I_2$ is given by

$$P(I_2) = P(Y_4) + P(Y_5) - P(Y_4)P(Y_5)$$
$$= 0.04 + 0.04 - (0.04)(0.04)$$
$$= 0.0784$$

FIGURE 10.3
Fault tree for Example 10.2.
where

\[ P(I_2), P(Y_4), \text{ and } P(Y_5) \] are the occurrence probabilities of events \( I_2, Y_4 \) and \( Y_5 \), respectively.

By using the above calculated and given data values and Chapter 4, we get

\[
P(T) = 1 - [1 - P(Y_1)][1 - P(I_1)][1 - P(I_2)][1 - P(Y_6)]
\]

\[
= 1 - (1 - 0.04)(1 - 0.04)(1 - 0.04)(1 - 0.04)
\]

\[
= 0.2172
\]

where

\[ P(T), P(Y_1) \text{ and } P(Y_6) \] are the occurrence probabilities of events \( T, Y_1 \), and \( Y_6 \), respectively.

Thus, the occurrence probabilities of events \( T, Y_1 \), and \( I_2 \) are 0.2172, 0.0784, and 0.0784, respectively. Figure 10.3 fault tree with specified and calculated fault event occurrence probability values is shown in Figure 10.4.

### 10.9.3 Maintenance Personnel Performance Simulation (MAPPS) Model

This is a computerized, stochastic, task-oriented human behavioral model. It was developed by the Oak Ridge National Laboratory to provide estimates of nuclear power plant maintenance manpower performance.
measures [23]. The development of this model was sponsored by the U.S. NRC, and the main objective for its development was the pressing need for and lack of a human reliability-related data bank pertaining to nuclear power plant maintenance activities for use in conducting probabilistic risk assessment studies [23].

Some of the performance measures estimated by the MAPPS model are identification of the most and least likely error-prone sub elements, probability of successfully accomplishing the task of interest, probability of an undetected error, the task duration time, and maintenance team stress profiles during task execution. Needless to say, the MAPPS model/method is an excellent tool to estimate important maintenance parameters, and its flexibility allows it to be useful for various applications concerned with nuclear power plant maintenance activity.

Additional information on this model/method is available in Reference 23.

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10.10 Problems

1. Write an essay on human factors and human error in nuclear power plant maintenance.

2. Discuss at least four types of human factors engineering maintenance-related shortcomings/problems in nuclear power plant systems.

3. What are the elements relating to human performance that can contribute to an effective maintenance program in nuclear power plants?

4. Discuss at least three human factors methods for assessing and improving nuclear power plant maintainability.

5. Discuss at least five facts, figures, and examples that are directly or indirectly concerned with human error in nuclear power plant maintenance.

6. What are the main causes for the occurrence of human error in nuclear power plant maintenance?

7. What are the maintenance tasks most susceptible to human error in nuclear power plants?

8. Discuss useful guidelines for human error reduction and prevention in nuclear power plant maintenance.

9. Prove Equations 10.4, 10.9, and 10.10 by using Equations 10.1 through 10.3.

10. What are the types of human errors that can occur in digital plant protection system maintenance tasks?
References


