1 Introduction

1.1 BACKGROUND

Since the Industrial Revolution, maintenance of engineering equipment in the field environment has been a challenging issue. Although over the years impressive progress has been made in maintaining equipment in the field environment, maintenance of equipment is still a challenging issue with regard to factors such as cost, complexity, competition, and size. Each year billions of dollars are spent to maintain engineering systems throughout the world. For example, U.S. industry spends over $300 billion on plant maintenance and operation annually [1]. It is estimated that about 80% of this amount is spent to rectify the chronic failure of systems, machines, and humans.

Over the years, the occurrence of human errors in maintenance activity has been following an upward trend due to various factors, and their (human errors) consequences could be very serious. Two examples of these consequences are the Three Mile Island nuclear accident and the crash of a DC-10 aircraft at O'Hare Airport in Chicago that killed 272 people on board [2–5]. Since the late 1920s, a large number of publications directly or indirectly related to human reliability, error, or human factors in engineering maintenance have appeared. A list of over 200 such publications is provided in the Appendix.

1.2 HISTORY

This section presents an overview of historical developments in human factors, human reliability and error, and engineering maintenance.

1.2.1 Human Factors

The history of human factors may be traced back to 1898, when Frederick W. Taylor conducted various studies to determine the most appropriate designs for shovels [6]. In 1911, Frank B. Gilbreth studied bricklaying, and that resulted in the invention of a scaffold. As the result of this invention, the number of bricks laid per hour by bricklayers almost tripled (i.e., from 120 to 350 bricks per hour).

In 1918, the United States government established laboratories at the Wright-Patterson Air Force Base and the Brooks Air Force Base for conducting human factors-related research [7]. The period between World War I and World War II witnessed significant growth in disciplines such as industrial engineering and industrial psychology. By 1945, human factors engineering was recognized as a specialized discipline of engineering. In the 1950s and 1960s, the United States military and space programs further increased the importance of human factors in system design.

Currently, there are hundreds of published documents on various aspects of human factors in the form of textbooks, technical reports, design specifications, and articles. In addition, many research journals, annual conferences, and professional societies around the world are devoted to the field of human factors.

Additional information on the historical developments in human factors is available in Refs. [7–10].

1.2.2 Human Reliability and Error

The history of human reliability and error can be traced back to the late 1950s when H.L. Williams pointed out that the reliability of the human element must be included in the system reliability prediction; otherwise the predicted system reliability would not depict the real picture [11]. In 1960, Shapero et al. pointed out that a large proportion of equipment failures (20%–50%) are due to human error [12]. In the same year, a study conducted by W. I. LeVan also pointed out that 23%–45% of equipment failures were due to human error [13].

In 1973, a well-known journal titled *IEEE Transactions on Reliability* published a special issue on human reliability. In 1986, the first book on human reliability, titled *Human Reliability: With Human Factors,* was published [14]. Additional information on historical developments in human reliability and error is available in Refs. [14–16] and a comprehensive list of publications on the subject up to 1994 is given in Ref. [17].

1.2.3 Engineering Maintenance

Although the history of engineering maintenance may be traced back to the development of the steam engine by James Watt (1735–1819) in 1769 in Great Britain, in the United States a magazine titled *Factory* that first appeared in 1882 played a critical role in the development of the maintenance field [18, 19]. In 1886, a book titled *Maintenance of Railways* was published in the United States [20].

The term *preventive maintenance* was coined in the 1950s and a handbook on maintenance engineering was published in 1957 [21]. Over the years a vast amount of published literature on engineering maintenance in the form of textbooks, technical reports, and articles have appeared and today many institutions throughout the world offer academic programs on engineering maintenance.

1.3 HUMAN RELIABILITY, ERROR, AND HUMAN FACTORS IN ENGINEERING MAINTENANCE-RELATED FACTS AND FIGURES

Some of the facts and figures directly or indirectly concerned with human reliability, error, and human factors in engineering maintenance are as follows:

- Each year U.S. industry spends over $300 billion on plant maintenance and operations, and about 80% of this amount is spent to rectify the chronic failure of people, systems, and machines [1].

- The typical size of a plant maintenance department in manufacturing organizations varied from around 5% to 10% of the total operating workforce [22].
- For the period 1982–1991, a study of safety issues concerning onboard fatalities of jet fleets worldwide reported that maintenance and inspection were the second most important safety issue, with 1481 onboard fatalities [23, 24].
- In 1993, a study of 122 maintenance events involving human factors reported that there were four types of maintenance errors: omissions (56%), wrong installations (30%), wrong parts (8%), and others (6%) [23, 25].
- A study of 213 maintenance problem-related reports, reported that approximately 25% were due to human error [26].
- 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 wrong material [27].
- A study of maintenance errors in missile operations grouped the error causes under six categories: dials and controls (misread, misset) (38%), wrong installation (28%), loose nuts/fittings (14%), inaccessibility (8%), and miscellaneous (17%) [5, 14].
- In 1985, 520 people were killed in a Japan Airlines Boeing 747 jet accident because of wrong repair [28, 29].
- A study of various maintenance tasks, including removing, adjusting, and aligning, reported an average human reliability of 0.9871 [30].
- 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 [4].
- In 1979, 272 people were killed in a DC-10 aircraft accident in Chicago because of wrong procedures followed by maintenance workers [5].
- A study of over 4400 maintenance history records covering the period from 1992–1994, 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 [31, 32].
- According to Ref. [33] maintenance error contributes to 15% of air carrier accidents and costs the United States industry over 1 billion dollars annually.
- In 1988 in the United Kingdom, 30 people died and 69 were injured seriously at the Clapham Junction railways accident due to a maintenance error in wiring [34].
- 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 [35].
- According to a Boeing study, 19.1% of in-flight engine shutdowns are caused by maintenance error [33].
- 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 [36].
- A study reported that maintenance and inspection are the factors in approximately 12% of major aircraft accidents [37, 38].

- In 1988, the upper cabin structure of a Boeing 737-200 aircraft was ripped away during a flight because of structural failure, basically due to the failure of maintenance inspectors to identify over 240 cracks in the aircraft skin during the inspection process [39, 40].

1.4 TERMS AND DEFINITIONS

This section presents some useful terms and definitions directly or indirectly related to human reliability, error, and human factors in engineering maintenance [41–50]:

- **Maintenance.** This is all actions necessary for retaining an item/equipment in, or restoring it to, a specified condition.
- **Human reliability.** This is the probability of accomplishing a specified task successfully by humans at any required stage in system operation within a defined minimum time limit (if the time requirement is specified).
- **Human factors.** This is a body of scientific-related facts concerning the characteristics of humans. The term includes all psychosocial and biomedical considerations. It also includes, but is in no way restricted to, personnel selection, training principles and applications in the area of human engineering, human performance evaluation, aids for task performance, and life support.
- **Human error.** This is the failure to perform a specified task (or the performance of a forbidden action) that could result in disruption of scheduled operations or damage to equipment and property.
- **Corrective maintenance.** This is the unscheduled maintenance or repair to return equipment/system/items to a specified state and performed because maintenance personnel or users perceived deficiencies or failures.
- **Inspection.** This is the qualitative observation of an item's condition or performance.
- **Safety.** This is conservation of human life and its effectiveness, and the prevention of damage to items as per specified mission requirements.
- **Human performance.** This is a measure of actions and failures under given conditions.
- **Preventive maintenance.** This is all actions performed on a planned, periodic, and specific schedule for keeping a piece of equipment in stated working condition through the process of reconditioning and checking. These actions are precautionary steps undertaken for reducing or forestalling the probability of failures or an unacceptable level of degradation in later service, rather than rectifying them after their occurrence.
- **Failure.** This is the inability of an item/equipment/system to perform its stated function.
- **Accident.** This is an event that involves damage to a specified system that suddenly disrupts the current or potential system output.
- **Human performance reliability.** This is the probability that a human will satisfy all stated human functions subject to specified conditions.
- **Maintenance person.** This is an individual who performs preventive maintenance and responds to a user's service call to a repair facility, and

carry out appropriate corrective maintenance on an item/equipment. Some of the other names used for this individual are field engineer, service person, repair person, technician, and mechanic.
- **Continuous task.** This is a task/job that involves some kind of tracking activity (e.g., monitoring a changing situation).
- **Mission time.** This is that element of uptime required to carry out a given mission profile.
- **Hazardous condition.** This is a condition with a potential to threaten human life, properties, health, or the environment.
- **Risk.** This is the probable rate of occurrence of a hazardous condition and the degree of severity of the harm.
- **Maintainability.** This is the probability that a failed item will be restored to satisfactorily working condition.
- **Reliability.** This is the probability that an item will perform its specified function adequately for the desired period when used according to the stated conditions.
- **Redundancy.** This is the existence of more than one means to carry out a stated function.

1.5 USEFUL INFORMATION ON HUMAN RELIABILITY, ERROR, AND HUMAN FACTORS IN ENGINEERING MAINTENANCE

This section lists selected publications, organizations, and data sources that are considered directly or indirectly useful for obtaining information on human reliability, error, and human factors in engineering maintenance.

1.5.1 Publications

These are listed under four distinct classifications: books, technical reports, conference proceedings, and journals.

1.5.1.1 Books

- Reason, J., Hobbs, A., *Managing Maintenance Error: A Practical Guide,* Ashgate Publishing, Aldershot, UK, 2003.
- Dhillon, B.S., *Human Reliability: With Human Factors,* Pergamon Press, New York, 1986.
- Patankar, M.S., Taylor, J.C., *Risk Management and Error Reduction in Aviation Maintenance,* Ashgate Publishing, Aldershot, UK, 2006.
- Whittingham, R.B., *The Blame Machine: Why Human Error Causes Accidents,* Elsevier Butterworth-Heinemann, Oxford, UK, 2004.
- Strauch, B. *Investigating Human Error: Incidents, Accidents, and Complex Systems,* Ashgate Publishing, Aldershot, UK, 2002.
- Corlett, E.N., Clark, T.S., *The Ergonomics of Workspaces and Machines,* Taylor and Francis, London, 1995.
- Karwowski, W., Marras, W.S., *The Occupational Ergonomics Handbook,* CRC Press, Boca Raton, FL, 1999.

- Sanders, M.S., McCormick, E.J., *Human Factors in Engineering and Design,* McGraw Hill, New York, 1993.
- Hall, S., *Railway Accidents,* Ian Allan Publishing, Shepperton, UK, 1997.
- Dhillon, B.S., *Engineering Maintenance: A Modern Approach,* CRC Press, Boca Raton, FL, 2002.

1.5.1.2 Technical Reports

- Report No. CAP 718, Human Factors in Aircraft Maintenance and Inspection, Prepared by the Safety Regulation Group, Civil Aviation Authority, London, UK. Available from the Stationery Office, P.O. Box 29, Norwich, UK.
- Circular 243–AN 151, Human Factors in Aircraft Maintenance and Inspection, International Civil Aviation Organization, Montreal, Canada, 1995.
- Report No. DOT/FRA/RRS-22, Federal Railroad Administration (FRA) Guide for Preparing Accident/Incident Reports, FRA Office of Safety, Washington, D.C., 2003.
- Maintenance Error Decision Aid (MEDA), Developed by Boeing Commercial Airplane Group, Seattle, Washington, 1994.
- Report No. NTSR/SIR-94/02, Maintenance Anomaly Resulting in Dragged Engine During Landing Rollout, Northwest Airlines Flight 18, New Tokyo International Airport, March 2, 1994, National Transportation Safety Board (NTSB), Washington, D.C., 1995.
- Hobbs, A., Williamson, A., Aircraft Maintenance Safety Survey-Results, Report, Australian Transport Safety Bureau, Canberra, Australia, 2000.
- Seminara, J.L., Parsons, S.O., Human Factors Review of Power Plant Maintenance, Report No. EPRI NP-1567, Electric Power Research Institute (EPRI), Palo Alto, CA, 1981.
- WASH-1400, Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, U.S. Nuclear Regulatory Commission, Washington, D.C., 1975.
- Nuclear Power Plant Operating Experience, from the IAEA/NEA Incident Reporting System 1996–1999, Report, Organization for Economic Co-operation and Development (OECD), 2 rue Andre-Pascal, 75775 Paris Cedex 16, France, 2000.
- Report No. DOC 9824-AN/450, Human Factors Guidelines for Aircraft Maintenance Manual, International Civil Aviation Organization (ICAO), Montreal, Canada, 1993.
- Report No. 2–97, Human Factors in Airline Maintenance: A Study of Incident Reports, Bureau of Air Safety Investigation (BASI), Department of Transport and Regional Development, Canberra, Australia, 1997.

1.5.1.3 Conference Proceedings

- Proceedings of the Human Factors and Ergonomics Society Conference, 1997.

- Proceedings of the Airframe/Engine Maintenance and Repair Conference, 1998.
- Proceedings of the Annual Reliability and Maintainability Symposium, 2001.
- Proceedings of the International Conference on Design and Safety of Advanced Nuclear Power Plants, 1992.
- Proceedings of the IEEE 6th Annual Human Factors Meeting, 1997.
- Proceedings of the 5th Federal Aviation Administration (FAA) Meeting on Human Factors Issues in Aircraft Maintenance and Inspection, 1991.
- Proceedings of the 48th Annual International Air Safety Seminar, 1995.
- Proceedings of the 9th International Symposium on Aviation Psychology, 1997.
- Proceedings of the 15th Symposium on Human Factors in Aviation Maintenance, 2001.
- Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics, 1996.

1.5.1.4 Journals

- *International Journal of Industrial Ergonomics*
- *Reliability Engineering and System Safety*
- *Safety Science*
- *ATEC Journal*
- *Human Factors*
- *Rail International*
- *Human Factors in Aerospace and Safety*
- *Maintenance Technology*
- *Industrial Maintenance and Plant Operation*
- *Journal of Quality in Maintenance Engineering*
- *Maintenance Journal*
- *Journal of Occupational Accidents*
- *Aeronautical Journal*
- *International Journal of Man-Machine Studies*
- *Asia Pacific Air Safety*
- *Ergonomics*
- *Aviation Mechanics Bulletin*
- *The CRM Advocate*
- *Applied Ergonomics*
- *Accident Prevention and Analysis*
- *Journal of Railway and Transport*
- *Human Factors and Ergonomics in Manufacturing*
- *Modern Railways*
- *Naval Engineers Journal*
- *Maintenance and Asset Management Journal*
- *Nuclear Safety*

1.5.2 Data Sources

Some of the sources that could be useful, directly or indirectly, in obtaining human reliability, error, and human factors in engineering maintenance-related data are as follows:

- National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia, USA.
- Stewart, C., The Probability of Human Error in Selected Nuclear Maintenance Tasks, Report No. EGG-SSDC-5586, Idaho National Engineering Laboratory, Idaho Falls, Idaho, 1981.
- Gertman, D.I., Blackman, H.S., *Human Reliability and Safety Analysis Data Handbook,* John Wiley and Sons, New York, 1994.
- Data on Equipment Used in Electric Power Generation, Equipment Reliability Information System (ERIS), Canadian Electrical Association, Montreal, Quebec, Canada.
- GIDEP Data, Government Industry Data Exchange Program (GIDEP) Operations Center, Fleet Missile Systems, Analysis, and Evaluation, Department of Navy, Corona, California.
- Schmidtke, H., Editor, *Ergonomic Data for Equipment Design,* Plenum Press, New York, 1984.
- Dhillon, B.S., *Human Reliability: With Human Factors,* Pergamon Press, New York, 1986 (this book lists over 20 sources for obtaining human reliability/error data).
- Boff, K.R., Lincoln, J.E., *Engineering Data Compendium: Human Perception and Performance,* Vols. 1–3, Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, Ohio, 1988.
- Defense Technical Information Center, DTIC-FDAC, 8725 John K. Kingman Road, Suite 0944, Fort Belvoir, Virginia.
- Dhillon, B.S., *Human Error Data Banks, Microelectronics and Reliability,* Vol. 30, 1990, pp. 963–971.
- DOD-HDBK-743A, Anthropometry of U.S. Military Personnel, Department of Defense, Washington, D.C.
- MIL-HDBK-759B, Human Factors Engineering Design for Army Material, Department of Defense, Washington, D.C.

1.5.3 Organizations

Some of the organizations that could be useful, directly or indirectly, to obtain human reliability, error, and human factors in engineering maintenance-related information are as follows:

- International Civil Aviation Organization, 999 University Street, Montreal, Quebec, Canada
- Society for Maintenance and Reliability Professionals, 401 N. Michigan Avenue, Chicago, Illinois.

- Japan Institute of Plant Maintenance, Shuwa Shiba-Koen-3-Chome Bldg., 3-1-38, Shiba-Koen, Minato-Ku, Tokyo, Japan
- Civil Aviation Safety Authority, North Bourne Avenue and Barry Drive Intersection, Canberra, Australia
- Transportation Safety Board of Canada, 330 Spark Street, Ottawa, Ontario, Canada
- Maintenance Engineering Society of Australia (MESA), 11 National Circuit, Barton, ACT, Australia
- Airplane Safety Engineering Department, Boeing Commercial Airline Group, The Boeing Company, 7755 E. Marginal Way South, Seattle, Washington.
- Federal Railroad Administration, 4601 N. Fairfax Drive, Suite 1100, Arlington, Virginia.
- National Research Council, 2101 Second Street, SW, Washington, D.C.
- Society for Machinery Failure Prevention Technology, 4193 Sudley Road, Haymarket, Virginia.
- Transportation Research Board, 2101 Constitution Avenue, NW, Washington, D.C.
- American Institute of Plant Engineers, 539 S. Lexington Place, Anaheim, California.
- Society of Logistics Engineers, 8100 Professional Place, Suite 211, Hyattsville, Maryland.

1.6 SCOPE OF THE BOOK

Just like any other areas of engineering, engineering maintenance is also subjected to human errors. In recent years increasing attention has been given to human errors in the maintenance activity due to various factors, including cost and serious consequences such as the Three Mile Island Nuclear accident and the crash of a DC-10 aircraft at O'Hare Airport in Chicago.

Over the years, a large number of publications on human error, reliability, and human factors in engineering maintenance have appeared basically in the form of journal and conference proceedings articles or technical reports. At present, to the best of the author's knowledge, there is no book that covers all these three topics including maintenance safety within its framework. This book not only attempts to provide up-to-date coverage of the on-going efforts in human reliability, error, and human factors in engineering maintenance, but also covers useful developments in the general areas of human factors, reliability, and error.

Finally, the main objective of this book is to provide professionals concerned with human reliability, error, and human factors in engineering maintenance information that could be useful to minimize or eliminate the occurrence of human error in this area. The book will be useful to many individuals, including engineering professionals working in the area of maintenance, maintenance engineering researchers and instructors, reliability, safety, and human factors professionals, and maintenance engineering administrators.

1.7 PROBLEMS

1. Write an essay on human reliability, error, and human factors in engineering maintenance.
2. Define the following terms:
   - Human factors
   - Human reliability
   - Maintenance
3. List at least five facts and figures concerned with human error/reliability in engineering maintenance.
4. Discuss historical developments in the following two areas, separately:
   - Human reliability
   - Human factors
5. What is the difference between accident and risk?
6. Define the following terms:
   - Human error
   - Maintenance person
7. List at least five journals considered useful for obtaining human reliability and error in engineering maintenance-related information.
8. List at least seven of the most important organizations for obtaining human reliability, error, and human factors in engineering maintenance-related information.
9. What is the difference between preventive and corrective maintenance?
10. List at least six books considered most useful for obtaining, directly or indirectly, human reliability, error, and human factors in engineering maintenance-related information.

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