Springer Series in Reliability Engineering

B. S. Dhillon

Human Reliability, Error, and Human Factors in Power Generation

Springer

Springer Series in Reliability Engineering

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Springer

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ISSN 1614-7839 ISSN 2196-999X (electronic)
ISBN 978-3-319-04018-9 ISBN 978-3-319-04019-6 (eBook)
DOI 10.1007/978-3-319-04019-6
Springer Cham Heidelberg New York Dordrecht London

Library of Congress Control Number: 2013956804

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

This book is affectionately dedicated to my granddaughter, Sianna

Preface

Each year billions of dollars are spent in the area of power generation to design, construct/manufacture, operate, and maintain various types of power systems around the globe. Many times such systems fail due to human error. For example, during the period 1990–1994 about 27 % of commercial nuclear power plants outages in the United States resulted from human error.

Needless to say, human reliability, error, and human factors in the area of power generation have been receiving increasing attention over the years. Although over the years a large number of journal and conference proceedings articles related to human reliability, error, and human factors in power generation have appeared, but to the best of the author's knowledge, there is no specific book on the topic. This causes a great deal of difficulty to information seekers because they have to consult many different and diverse sources.

Thus, the main objective of this book is to combine these topics into a single volume and eliminate the need to consult many diverse sources to obtain desired information. The sources of most of the material presented are listed in the reference section at the end of each chapter. These will be useful to readers if they desire to delve more deeply into a specific area or topic of interest.

The book contains a chapter on mathematical concepts and another chapter on introductory human factors, human reliability, and human error concepts considered useful to understand contents of subsequent chapters.

The topics covered in the book are treated in such a manner that the reader will require no previous knowledge to understand the contents. At appropriate places, the book contains examples along with their solutions, and at the end of each chapter there are numerous problems to test the reader's comprehension. An extensive list of publications dating from 1971 to 2012, directly or indirectly on human reliability, error, and human factors in power generation, is provided at the end of this book to give readers a view of intensity of developments in the area.

The book is composed of 11 chapters. Chapter 1 presents various introductory aspects, directly or indirectly related to human reliability, error, and human factors in power generation including facts, figures, and examples; terms and definitions; and sources for obtaining useful information on human reliability, error, and human factors in power generation.

Chapter 2 reviews mathematical concepts considered useful to understanding subsequent chapters. Some of the topics covered in the chapter are sets, Boolean algebra laws, probability properties, useful definitions, and probability distributions. Chapter 3 presents various introductory human factors, reliability, and error concepts. Chapter 4 presents six general methods considered useful to perform human reliability and error analysis in power generation. These methods are error-cause removal program, man–machine systems analysis, failure modes and effect analysis, probability tree method, Markov method, and fault tree analysis.

Chapter 5 is devoted to specific human reliability analysis methods for nuclear power plants. The methods presented in the chapter are a technique for human event analysis (ATHEANA), cognitive reliability and error analysis method (CREAM), technique for human error rate prediction (THERP), success likelihood index method-multiattribute utility decomposition (SLIM-MAUD), accident sequence evaluation program (ASEP), human cognitive reliability model (HCR), standardized plant analysis risk-human reliability analysis (SPAR-H), and human error assessment and reduction technique (HEART).

Chapters 6 and 7 present various important aspects of human factors and human error in power generation, respectively. Chapter 8 is devoted to human factors in control systems. It covers topics such as control room deficiencies that can lead to human error, common problems associated with controls and displays and their corrective measures, human factors guidelines for digital control system displays, and human engineering discrepancies in control room visual displays.

Chapter 9 covers various important aspects of human factors in power plant maintenance, including power plant systems' human factors engineering maintenance-related shortcomings, advantages of human factors engineering applications in power plants, and human factors methods to assess and improve power plant maintainability. Chapter 10 is devoted to human error in power plant maintenance. Some of the topics covered in the chapter are facts and figures, maintenance tasks most susceptible to human error in power generation, useful guidelines to reduce and prevent human errors in power plant maintenance, and methods for performing human error analysis in power plant maintenance.

Finally, Chap. 11 presents a total of six mathematical models for performing human reliability and error analysis in power generation.

The book will be useful to many individuals, including engineering professionals working in the area of power generation, power generation administrators, engineering undergraduate and graduate students, power system engineering researchers and instructors; reliability, safety, human factors, and psychology professionals; and design engineers and associated professionals.

The author is deeply indebted to many individuals, including family members, friends, colleagues, and students for their invisible input. The unseen contributions of my children also are appreciated. Last but not least, I thank my wife, Rosy, my other half and friend, for typing this entire book and timely help in proofreading.

Ottawa, Ontario B. S. Dhillon

Contents

Chapter 1
Introduction

1.1 Background

Over the years, since the way to generate electricity discovered by M. Faraday in the United Kingdom in the early part of the nineteenth century, the use of electricity has been continuously increasing. Each year, a vast sum of money is being spent in the area of power generation to design, construct/manufacture, operate, and maintain various types of power systems around the globe. Nuclear power plants are one example of such systems. They generate around 16 % of the world's electricity, and there are over 440 commercial nuclear reactors operating in 30 countries, with another 65 reactors under construction [1].

Needless to say, many times, such systems fail due to human error. For example, during the period 1990–1994, about 27 % of commercial nuclear plants outages in the United States resulted from human error [2]. Since 1971, a large number of publications directly or indirectly related to human reliability, error, or human factors in power generation have appeared. A list of over 240 such publications is provided in the Appendix.

1.2 Human Reliability, Error, and Human Factors in Power Generation-Related Facts, Figures, and Examples

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

- During the period 1969–1986, about 54 % of the incidents due to human errors in Japan resulted in automatic shutdown of nuclear reactors and 15 % of that resulted in power reduction [3].

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- A study of 255 shutdowns that occurred in Korean nuclear power plants during the period 1978–1992 reported that 77 of these shutdowns were human induced [4, 5].
- During the period 1990–1994, around 27 % of the commercial nuclear power plant outages in the United States were the result of human error [2].
- A study of 143 occurrences of operating US commercial nuclear power plants during the period from February 1975 to April 1975 revealed that about 20 % of the occurrences were due to operator errors [6, 7].
- A study of over 4,400 maintenance-related history records concerning a boiling water reactor (BWR) nuclear power plant covering the period from 1992 to 1994 revealed that about 7.5 % of all failure records could be attributed to human errors related to maintenance activities [8, 9].
- In 1990, in the area of nuclear power generation, a study of 126 human error-related significant events revealed that about 42 % of the problems were linked to modification and maintenance [10].
- As per Ref. [11], during the period from 1965 to 1995, a total of 199 human errors occurred in Japanese nuclear power plants, out of which 50 of them were concerned with maintenance tasks.
- As per Refs. [12, 13], operation errors associated with control centres in fossil-fired steam generating power plants in the United States could result in up to 3.85 % of plants' unavailability.
- As per Ref. [14], a study by the United States Nuclear regulatory Commission (NRC) of Licensee Reports reported that around 65 % of nuclear system failures involve human error [15].
- As per Refs. [10, 16], a number of studies reported that between 55 and 65 %, human performance-related problems surveyed in the area of power generation were concerned with maintenance activities.
- As per Refs. [12, 17], about 70 % of nuclear power plant operation errors appear to have a human factor origin.
- As per Ref. [18], 25 % of unexpected shutdowns in Korean nuclear power plants were due to human errors, out which more than 80 % of human errors resulted from usual testing and maintenance tasks.
- As per Ref. [11], maintenance errors account for around 60 % of the annual power loss due to human errors in fossil power plants.
- As per Ref. [19], the major incident/accident reports of nuclear power plants in Korea indicate that about 20 % of the total events occur due to human error.
- As per Ref. [20], in 1979, the Three Mile Island nuclear power plant accident in the United States was the result of human-related problems.
- In 1986, Chernobyl nuclear power plant accident in Ukraine, widely regarded as the worst accident in the history of nuclear power, was also the result of human-related problems [20].
- As per Ref. [21], in the state of Florida, on Christmas Day in 1989, two nuclear reactors were shut down due to maintenance error and caused rolling blackouts.
- In the late 1990s, a blast at the Ford Rouge power plant in Dearborn, Michigan, due to a maintenance error killed six workers and injured many others [22, 23].

1.3 Terms and Definitions

This section presents some useful terms and definitions directly or indirectly related to human reliability, error, and human factors in power generation [23–31]:

- **Human factors**. This is a study of the interrelationships between humans, the tools they utilize, and the surrounding environment in which they work and live.
- **Power system reliability**. This is the degree to which the performance of the elements in a bulk system results in electrical energy being delivered to customers within the specified standards and in the amount needed.
- **Human error**. This is the failure to perform a specified task (or the performance of a forbidden action) that could lead to disruption of scheduled operations or result in damage to equipment and property.
- **Continuous task**. This is a task that involves some kind of tracking activity (e.g. monitoring a changing condition or situation).
- **Human performance**. This is a measure of failures and actions under specified conditions.
- **Human reliability.** This is the probability of accomplishing a task successfully by humans at any required stage in system operation within a specified minimum time limit (i.e. if the time requirement is stated).
- **Failure**. This is the inability of an equipment/system/item to carry out its specified function.
- **Mission time**. This is that element of uptime required to perform a specified mission profile.
- **Maintenance**. This is all actions appropriate to retain an item/equipment in, or restoring it to, a stated condition.
- **Reliability**. This is the probability that an item will carry out its stated function satisfactorily for the desired period when used according to the specified conditions.
- **Man function**. This is that function which is allocated to the system's human element.
- **Unsafe behaviour**. This is the manner in which a person carries out actions that are considered unsafe to himself/herself or others.
- **Human error consequence**. This is an undesired consequence of human failure.
- **Maintainability**. This is the probability that a failed equipment/system/item will be restored to satisfactorily working condition.
- **Maintenance person**. This is a person who carries out preventive maintenance and responds to a user's service call to a repair facility and performs appropriate corrective maintenance on an equipment/item/system. Some of the other names used for this individual are repair person, technician, field engineer, and service person.
- **Redundancy**. This is the existence of more than one means to perform a stated function.
- **Downtime**. This is the time during which the item/equipment/system is not in a condition to carry out its defined mission.

- **Useful life**. This is the length of time an item/equipment/system functions within an acceptable level of failure rate.
- **Safety**. This is conservation of human life and its effectiveness and the prevention of damage to items as per stated mission requirements.

1.4 Useful Information on Human Reliability, Error, and Human Factors in Power Generation

This section lists books, journals, technical reports, conference proceedings, data sources, and organizations that are considered directly or indirectly useful for obtaining information on human reliability, error, and human factors in the area of power generation.

1.4.1 Books

Some of the books, directly or indirectly, concerned with human reliability, error, and human factors in power generation are as follows:

- Whittingham, R.B., The Blame Machine: Why Human Error Causes Accidents, Elsevier Butterworth-Heinemann, Oxford, U.K., 2004.
- Dekker, S., Ten Questions About Human Error: A New View of Human Factors and System Safety, Lawrence Erlbaum Associates, Mahwah, New Jersey, 2005.
- Dhillon, B.S., Human Reliability: with Human Factors, Pergamon Press, New York, 1986.
- Salvendy, G., Editor, Handbook of Human Factors and Ergonomics, John Wiley and Sons, New York, 2006.
- Proctor, R.W.,Van Zandt, T., Human Factors in Simple and Complex Systems, CRC Press, Boca Raton, Florida, 2008.
- Dhillon, B.S., Human Reliability, Error, and Human Factors in Engineering Maintenance, CRC Press, Boca Raton, Florida, 2009.
- Grigsby, L.E., editor, Electric Power Generation, Transmission, and Distribution, CRC Press, Boca Raton, Florida 2007.
- Dhillon, B.S., Power System Reliability, Safety, and Management, Ann Arbor Science Publishers, Ann Arbor, Michigan, 1983.
- Cepin, M., Assessment of Power System Reliability: Methods and Applications, Springer, London, 2011.
- Strauch, B., Investigating Human Error: Incidents, Accidents, and Complex Systems, Ashgate Publishing, Aldershot, UK, 2002.
- Reason, J., Hobbs, A., Managing Maintenance Error: A Practical Guide, Ashgate Publishing, Aldershot, UK, 2003.

- Kletz, T.A., An Engineer's View of Human Error, Taylor and Francis, New York, 2001.
- Peters, G.A., Peters, B.J., Human Error: Causes and Control, CRC Press, Boca Raton, Florida, 2006.
- Oborne, D.J., Ergonomics at Work: Human Factors in Design and Development, John Wiley and Sons, New York, 1995.
- Willis, H.E., Scott, W.G., Distributed Power Generation: Planning and Evaluation, Marcel Dekker, New York, 2000.
- Corlett, E.N., Clark, T.S., The Ergonomics of Workspaces and Machines, Taylor and Francis, London, 1995.

1.4.2 Journals

Some of the journals that time to time publish articles, directly or indirectly, concerned with human reliability, error, and human factors in power generation are listed below.

- Reliability Engineering and System Safety.
- IEEE Transactions on Power Apparatus and Systems.
- IEEE Transaction on Reliability.
- IEEE Power & Energy Magazine.
- Human Factors.
- International Journal of Man–Machine Studies.
- Accident Prevention and Analysis.
- Nuclear Safety.
- Human Factors in Aerospace and Safety.
- Journal of Quality in Maintenance Engineering.
- Applied Ergonomics.
- Nuclear Engineering and Design.
- IEEE Transactions on Industry Applications.
- Journal of Risk and Reliability.
- Journal of Korean Nuclear Society.
- Power Engineering.
- International Journal of Reliability, Quality, and Safety Engineering.
- Human Factors and Ergonomics in Manufacturing.
- Nuclear Europe Worldscan.
- Ergonomics.
- IEEE Transactions on Power Delivery.
- IEEE Transactions on Systems, Man, and Cybernetics.
- International Journal of Power and Energy Systems.
- Nuclear Energy and Engineering.
- Electric Power Systems Research.

1.4.3 Technical Reports

Some of the technical reports, directly or indirectly, concerned with human reliability, error, and human factors in power generation are as follows:

- Kolaczkowshi, A., Forester, J., Lois, E., Cooper, S., Good Practices for Implementing Human Reliability Analysis (HRA), Report No. NUREG-1792, United States Nuclear Regulatory Commission, Washington, D.C., April 2005.
- Nuclear Power Plant Operating Experience, from the IAEA/NEA Incident Reporting System, Report, Organization for Economic Co-operation and Development (OECD), 2 rue Andre-Pascal, 7575 Paris Cedex 16, France, 2000.
- "An Analysis of 1990 significant Events", Report No. INP091-018, Institute of Nuclear Power Operations (INPO), Atlanta, Georgia, 1991.
- "Assessment of the Use of Human Factors in the Design of Fossil-Fired Steam Generating Systems", Report No. EPRI CS-1760, Electric Power Research Institute (EPRI), Palo Alto, California, 1981.
- Trager, T.A., Jr., Case Study Report on Loss of Safety System Function Events, Report No. AEOD/C504, United States Nuclear Regulatory Commission, Washington, D.C., 1985.
- "An Analysis of Root Causes in 1983 and 1984 Significant Event Reports", Report No. 85-027, Institute of Nuclear Power Operations, Atlanta, Georgia, July 1985.
- Seminara, J.L., Parsons, S.O., Human Factors Review of Power Plant Maintenance, Report No. EPRI NP-1567, Electric Power Research Institute, Palo Alto, California, 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.
- McCornack, R.L., Inspector Accuracy: A Study of the Literature, Report No. SCTM 53-61 (14), Sandia Corporation, Albuquerque, New Mexico, 1961.
- Maintenance Error Decision Aid (MEDA), Developed by Boeing Commercial Airplane Group, Seattle, Washington, 1994.

1.4.4 Conference Proceedings

Some of the conference proceedings that contain articles, directly or indirectly, concerned with human reliability, error, and human factors in power generation are listed below.

- Proceedings of the American Nuclear Society International Topical Meeting on Nuclear Power Plant Instrumentation Controls, and Human Machine Interface Technology, 2009.
- Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007.

- Proceedings of the International Conference on Nuclear Energy for New Europe, 2006.
- Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2005.
- Proceedings of the IEEE Power Engineering Society General Meeting, 2006.
- Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics, 2007.
- Proceedings of the International Conference on Nuclear Power Plant Aging, Availability Factor, and Reliability Analysis, 1985.
- Proceedings of the International Conference on Design and Safety of Advanced Nuclear Power Plants, 1992.
- Proceedings of the Annual Reliability and Maintainability Symposium, 2001.
- Proceedings of the Annual Symposium on Reliability, 1969.
- Proceedings of the IEEE International Conference on Human Interfaces in Control Rooms, 1999.

1.4.5 Data Sources

There are many sources to obtain human reliability and error data. Some of the sources that could be useful, directly or indirectly, for obtaining human reliability and error data in the area of power generation are as follows:

- Human Error Classification and Data Collection, Report No. IAEA-TEC DOC-538, International Atomic Energy Agency (IAEA), Vienna, Austria, 1990.
- Government Industry Data Exchange Program (GIDEP), GIDEP Operations Center, U.S. Department of Navy, Corona, California, USA.
- Stewart, C., The Probability of Human Error in Selected Nuclear Maintenance Tasks, Report No. EGG-SSDC-5580, Idaho National Engineering Laboratory, Idaho Falls, Idaho, USA, 1981.
- Dhillon, B.S., Human Reliability: With Human Factors, Pergamon Press, New York, 1986 (This book lists over 20 sources for obtaining human reliability-related data).
- 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 Center (ERIC), Canadian Electrical Association, Montreal, Quebec, Canada.
- Swain, A.D., Guttman, H.E., Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, Report No. NUREG/CR-1278, U.S. Nuclear Regulatory Commission, Washington, D.C., 1983.
- Collection and Classification of Human Reliability Data for Use in Probabilistic Safety Assessments, Report No. IAEA-TECDOC-1048, International Atomic Energy Agency, Vienna, Austria, 1998.

- Dhillon, B.S., Human Error Data Banks, Microelectronics and Reliability, Vol. 30, 1990, pp. 963–971.
- 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, USA, 1988.
- Schmidtke, H., Editor, Ergonomic Data for Equipment Design, Plenum Press, New York, 1984.
- National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia, USA.

1.4.6 Organizations

There are many organizations that collect human reliability, error, and human factor-related data. Some of the organizations that could be useful, directly or indirectly, to obtain human reliability, error, and human factors in power generation-related data are listed below.

- IEEE Power & Energy Society, 445 Hoes Lane, Piscataway, New Jersey, USA.
- Human Factors and Ergonomics Society, 1124 Montana Avenue, Suite B, Santa Monica, California, USA.
- American Nuclear Society, 555 North Kensington Avenue, La Grange Park, Illinois, USA.
- International Atomic Energy Agency, Wagramer Strasse 5, Vienna, Austria.
- Canadian Nuclear Society, 655 Bay Street, 17th Floor, Toronto, Ontario, Canada.
- National Research Council, 2101 Constitution Avenue, NW, Washington, D.C., USA.
- American Society for Quality, 600 North Plankinton Avenue, Milwaukee, Wisconsin, USA.
- American Society of Safety Engineers, 1800 E Oakton Street, Des Plaines, Illinois, USA.
- International System Safety Society, Unionville, Virginia, USA.
- IEEE Reliability Society, c/o IEEE Corporate Office, 3 Oak Avenue, 17th Floor, New York, USA.
- Society for Maintenance and Reliability Professionals, 401 N. Michigan Avenue, Chicago, Illinois, USA.
- Society for Machinery Failure Prevention Technology, 4193 Sudley Road, Haymarket, Virginia, USA.

1.5 Scope of the Book

Just like any other area of engineering, electrical power generation is also subjected to human-related problems. In recent years, increasing attention is being given to human-related problems in the area of power generation due to various factors, including cost and serious consequences such as a blast at the Ford Rouge power plant and the Three Mile Island Nuclear accident.

Over the years, a large number of publications, directly or indirectly, related to human reliability, error, and human factors in power generation have appeared. Almost all of these publications are in the form of conference proceedings or journal articles, or technical reports. At present, to the best of author's knowledge, there is no specific book that covers the topic of this book within its framework. This book attempts to provide up-to-date coverage not only of the ongoing effort in human reliability, error, and human factors in power generation, but also of useful developments in the general areas of human reliability, human error, and human factors.

Finally, the main objective of this book is to provide professionals concerned with human reliability, error, and human factors in power generation information that could be useful to reduce or eradicate altogether the occurrence of human errors in this area. The book will be useful to many individuals including engineering professionals working in the area of power generation, researchers and instructors involved with power systems, reliability, and human factors, safety professionals and administrators involved with power generation, and graduate students in the area of power generation and reliability engineering.

1.6 Problems

1. Define the following terms:
   - Human factors.
   - Human error.
   - Human reliability.
2. Write an essay on human reliability, error, and human factors in power generation.
3. List at least six facts and figures concerned with human error/reliability in power generation.
4. Compare the terms "human performance" and "human reliability".
5. List five most important organizations to obtain human error and human reliability in power generation-related information.
6. List at least six important books for obtaining, directly or indirectly, human reliability and error in power generation-related information.

7. Define the following four terms:
   - Power system reliability.
   - Unsafe behaviour.
   - Mission time.
   - Human error consequence.
8. List at least six sources for obtaining human reliability and error in power generation-related data.
9. List six most important journals to obtain human reliability and error in power generation-related information.
10. Define the following terms:
    - Continuous task.
    - Man function.
    - Downtime.

References

1. Nuclear Industry Association (NIA) (2013) Facts and figures, Carlton House, London
2. Varma V (1996) Maintenance training reduces human errors. Power Eng 100:44–47
3. Mishima S (1988) Human factors research program: long term plan in cooperation with government and private research centers. In: Proceedings of the IEEE conference on human factors and power plants, pp 50–54
4. Heo G, Park J (2010) A framework for evaluating the effects of maintenance-related human errors in nuclear power plants. Reliab Eng Syst Saf 95:797–805
5. Lee JW, Park GO, Park JC, Sim BS (1996) Analysis of error trip cases in Korean NPPs. J Korean Nucl Soc 28:563–575
6. Scott RL (1975) Recent occurrences of nuclear reactors and their causes. Nucl Saf 16:496–497
7. Husseiny AA, Sabry ZA (1980) Analysis of human factor in operation of nuclear power plants. Atomkernenergie Kerntechnik 36:115–121
8. Pyy P, Laakso K, Reiman L (1997) A study of human errors related to NPP maintenance activities. In: Proceedings of the IEEE sixth annual human factors meeting, pp 12.23–12.28
9. Pyy P (2001) An analysis of maintenance failures at a nuclear power plant. Reliab Eng Syst Saf 72:293–302
10. Reason J (1997) Human factors in nuclear power generation: a systems perspective. Nucl Eur Worldscan 17(5–6):35–36
11. Daniels RW (1985) The formula for improved plant maintainability must include human factors. In: Proceedings of the IEEE conference on human factors and nuclear safety, pp 242–244
12. Williams JC (1988) A data-based method for assessing and reducing human error to improve operational performance. In: Proceedings of the IEEE conference on human factors and power plants, pp 436–450
13. Assessment of the Use of Human Factors in the Design of Fossil-Fired Steam Generating Systems (1981) EPRI Report No. CS-1760, Electric Power Research Institute (EPRI), Palo Alto, California
14. Ryan GT (1988) A task analysis-linked approach for integrating the human factor in reliability assessments of nuclear power plants. Reliab Eng Syst Saf 22:219–234

15. Trager TA Jr (1985) Case study report on loss of safety system function events. Report No. AEOD/C 504, United States Nuclear Regulatory Commission (NRC), Washington, D.C
16. An Analysis of 1990 Significant Events (1991) Report No. INPO 91-018, Institute of Nuclear Power Operations (INPO), Atlanta, Georgia
17. An Analysis of Root Causes in 1983 and 1984 Significant Event Reports (1985) Report No. 85-027, Institute of Nuclear Power Operations (INPO), Atlanta, Georgia, July 1985
18. Heo G, Park J (2009) Framework of quantifying human error effects in testing and maintenance. In: Proceedings of the sixth American nuclear society international topical meeting on nuclear plant instrumentation, control, and human-machine interface technologies, pp 2083–2092
19. Kim J, Park J, Jung W, Kim JT (2009) Characteristics of test and maintenance human errors leading to unplanned reactor trips in nuclear power plants. Nucl Eng Des 239:2530–2536
20. Kawano R (1997) Steps toward the realization of human-centered systems: an overview of the human factors activities at TEPCO. In: Proceedings of the IEEE 6th annual human factors meeting, pp 13.27–13.32
21. Maintenance Error a Factor in Blackouts (1989) Miami Herald, Miami, Florida, 29 Dec, p 4
22. The UAW and the Rouge Explosion: A Pat on the Head (1999) Detroit news, Detroit, Michigan, 6 Feb, p 6
23. Kueck JD, Kirby BJ, Overholt PN, Markel LC (2004) Measurement practices for reliability and power quality. Report No. ORNL/TM-2004/91, June 2004. Available from the Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA
24. Omdahl TP (ed) (1988) Reliability, availability, and maintainability (RAM) dictionary. ASQC Quality Press, Milwaukee
25. McKenna T, Oliverson R (1997) Glossary of reliability and maintenance terms. Gulf Publishing Company, Houston
26. MIL-STD-721C, Definitions of terms for reliability and maintainability. Department of Defense, Washington, D.C
27. Naresky JJ (1970) Reliability definitions. IEEE Trans Reliab 19:198–200
28. Meister D (1966) Human factors in reliability. In: Ireson WG (ed) Reliability handbook. McGraw Hill Book Company, New York
29. MIL-STD-721B (1996) Definitions of effectiveness for reliability, maintainability, human factors, and safety. Department of Defense, Washington, D.C., August 1966. Available from the Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, Pennsylvania
30. MIL-STD-1908, Definitions of human factors terms. Department of Defense, Washington, D.C
31. Dhillon BS (1986) Human reliability: with human factors. Pergamon Press, New York

Chapter 2
Basic Mathematical Concepts

2.1 Introduction

Just like in other areas of science and engineering, mathematics also plays an important role in the area of human reliability, error, and human factors. The history of mathematics may be traced back to more than 2,200 years to the development of our day-to-day used number symbols. The very first evidence of the use of these symbols is found on stone columns erected around 250 BC by the Scythian emperor of India named Asoka [1].

However, the development of the probability field is relatively new, and its history may be traced back to the writings of Girolamo Cardano (1501–1576) in which he considered some interesting probability issues [1, 2]. Blaise Pascal (1623–1662) and Peirre de Fermat (1601–1665) solved the problem of dividing the winnings in a game of chance, independently and correctly [2]. The first formal treatise on probability based on the Pascal-Fermat correspondence was written by Christiaan Huygens (1629–1695) in 1657 [2]. Needless to say, additional information on historical developments in the area of mathematics is available in Refs. [1, 2].

This chapter presents basic mathematical concepts considered useful in performing human reliability and error analysis in the area of power generation.

2.2 Sets and Boolean Algebra Laws

A set may be defined as any well-defined collection or list of objects. Usually, the objects comprising the set are known as its elements. Normally, capital letters such as X, Y, and Z are used to denote sets and their elements by the lower-case letters such as a, b, and c.

Two basic set operations are referred to as the union of sets and the intersection of sets. Either of the following two symbols is used to denote the union of sets [3]:

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- $+$
- $\cup$

For example, if $X + Y = Z$, it simply means that all the elements in set X or in set Y or in both sets (i.e. X and Y) are contained in set Z.

Similarly, either of the following two symbols is used to denote the intersection of sets:

- $\cap$
- dot (.)

For example, if $A \cap B = C$, it simply means that set C contains all elements which belong to both sets A and B. However, when sets A and B have no common elements, then these two sets are referred to as mutually exclusive or disjoint sets or events.

Boolean algebra plays an important role in probability theory and reliability-related studies and is named after a mathematician named George Boole (1813–1864). Some of its laws are as follows [3–5]:

Cummutative Law

$$X + Y = Y + X \tag{2.1}$$

$$X.Y = Y.X \tag{2.2}$$

where
X is an arbitrary set or event.
Y is an arbitrary set or event.
$+$ denotes the union of sets.
. denotes the intersection of sets. It is to be noted that sometimes, Eq. (2.2) is written without the dot, but it still conveys the same meaning.

Associative Law

$$(XY)Z = X(YZ) \tag{2.3}$$

$$(X + Y) + Z = X + (Y + Z) \tag{2.4}$$

where
Z is an arbitrary set or event.

Idempotent Law

$$X + X = X \tag{2.5}$$

$$XX = X \tag{2.6}$$

Absorption Law

$$X + (XY) = X \tag{2.7}$$

$$X(X + Y) = X \tag{2.8}$$

Distributive Law

$$X(Y + Z) = XY + XZ \tag{2.9}$$

$$X + YZ = (X + Y)(X + Z) \tag{2.10}$$

2.3 Probability Definition and Properties

Probability may be defined as follows [4, 6]:

$$P(X) = \lim_{n \to \infty} \left(\frac{N}{n} \right) \tag{2.11}$$

where

$P(X)$ is the probability of occurrence of event X.

N is the number of times event X occurs in the n repeated experiments.

Some of the basic properties of probability are presented below [4, 6].

- The probability of occurrence of event, say Y, is

$$0 \le P(Y) \le 1. \tag{2.12}$$

- The probability of occurrence and non-occurrence of an event, say Y, is always

$$P(Y) + P(\bar{Y}) = 1 \tag{2.13}$$

where

$P(Y)$ is the probability of occurrence of event Y.

$P(\bar{Y})$ is the probability of non-occurrence of event Y.

- Probability of the sample space S is

$$P(S) = 1. \tag{2.14}$$

- Probability of negation of the sample space S is

$$P(\bar{S}) = 0. \tag{2.15}$$

- The probability of the union of m independent events is

$$P(Y_1 + Y_2 + \cdots + Y_m) = 1 - \prod_{i=1}^{m} (1 - P(Y_i)) \tag{2.16}$$

where

$P(Y_i)$ is the probability of occurrence of event Y_i; for $i = 1, 2, 3, \ldots, m$.

- The probability of the union of m mutually exclusive events is given by

$$P(Y_1 + Y_2 + \cdots + Y_m) = \sum_{i=1}^{m} P(Y_i). \tag{2.17}$$

- The probability of an intersection of m independent events is given by

$$P(Y_1 Y_2 \ldots Y_m) = P(Y_1)P(Y_2)\ldots P(Y_m). \tag{2.18}$$

Example 2.1 Assume that a system used in a power generation plant is composed of three subsystems Y_1, Y_2, and Y_3 and which must be operated by three independent operators. For the successful operation of the system, all the three operators must perform their tasks correctly. The reliabilities of operators, operating subsystems Y_1, Y_2, and Y_3 are 0.95, 0.92, and 0.9, respectively.

Calculate the probability of successful operation of the system.

By substituting the given data values in Eq. (2.18), we get

$$\begin{aligned} P(Y_1 Y_2 Y_3) &= P(Y_1)P(Y_2)P(Y_3) \\ &= (0.95)(0.92)(0.9) \\ &= 0.7866. \end{aligned}$$

Thus, the probability of successful operation of the system is 0.7866.

2.4 Useful Mathematical Definitions

This section presents five mathematical definitions considered useful to perform human reliability-related studies in the area of power generation.

2.4.1 Definition I: Probability Density Function

For a continuous random variable, the probability density function is defined by [6, 7]

$$f(t) = \frac{\mathrm{d}F(t)}{\mathrm{d}t} \tag{2.19}$$

where

t is time (i.e. a continuous random variable).

$f(t)$ is the probability density function. In the area of human reliability, it is often referred to as error density function.

$F(t)$ is the cumulative distribution function.

Example 2.2 Assume that the error probability at time t (i.e. cumulative distribution function) of a power generating system operator is expressed by

$$F(t) = 1 - e^{-\theta t} \tag{2.20}$$

where

θ is the constant error rate of the power generating system operator.

$F(t)$ is the cumulative distribution function or the operator error probability at time t.

Obtain an expression for the probability density function (i.e. in this case, the operator error density function) by using Eq. (2.19).

By inserting Eq. (2.20) into Eq. (2.19), we obtain

$$\begin{aligned} f(t) &= \frac{\mathrm{d}\left(1 - e^{-\theta t}\right)}{\mathrm{d}t} \\ &= \theta e^{-\theta t} \end{aligned} \tag{2.21}$$

Thus, Eq. (2.21) is the expression for the operator error density function.

2.4.2 Definition II: Cumulative Distribution Function

Cumulative distribution function for a continuous random variable is expressed by [6, 7]

$$F(t) = \int_{-\infty}^{t} f(y)\mathrm{d}y \tag{2.22}$$

where

y is a continuous random variable.

$f(y)$ is the probability density function.

For $t = \infty$ in Eq. (2.22), we get

$$\begin{aligned} F(\infty) &= \int_{-\infty}^{\infty} f(y)\mathrm{d}y \\ &= 1. \end{aligned} \tag{2.23}$$

It simply means that the total area under the probability density curve is always equal to unity.

Example 2.3 Prove Eq. (2.20) with the aid of Eq. (2.21).

Thus, for $t \geq 0$, by inserting Eq. (2.21) into Eq. (2.22), we obtain

$$\begin{aligned} F(t) &= \int_0^t \theta e^{-\theta t} \mathrm{d}t \\ &= 1 - e^{-\theta t}. \end{aligned} \tag{2.24}$$

Both Eqs. (2.20) and (2.24) are identical.

2.4.3 Definition III: Expected Value

The expected value of a continuous random variable is expressed by [6, 7]

$$E(t) = \int_{-\infty}^{\infty} t f(t) \mathrm{d}t \tag{2.25}$$

where

$E(t)$ is the expected value or mean value of the continuous random variable t. It is to be noted that in the area of human reliability and error, the expected value is known as the mean time to human error.

Example 2.4 Assume that a power generating system operator's error density function, for time $t \geq 0$, is expressed by Eq. (2.21) and the operator's error rate is 0.0005 errors/h. Calculate mean time to human error of the power generating system operator.

For $t \geq 0$, by inserting Eq. (2.21) into Eq. (2.25), we get

$$\begin{aligned} E(t) &= \int_0^{\infty} t\, \theta e^{-\theta t} \mathrm{d}t \\ &= \frac{1}{\theta}. \end{aligned} \tag{2.26}$$

By substituting the given data value for θ in Eq. (2.26), we obtain

$$\begin{aligned} E(t) &= \frac{1}{0.0005} \\ &= 2{,}000\,\mathrm{h}. \end{aligned}$$

Thus, the mean time to human error of the power generating system operator is 2,000 h.

2.4.4 Definition IV: Laplace Transform

The Laplace transform of the function $f(t)$ is defined by [8]

$$f(s) = \int_0^\infty f(t)e^{-st}\mathrm{d}t \tag{2.27}$$

where

s is the Laplace transform variable.
$f(s)$ is the Laplace transform of $f(t)$.
t is the time variable.

Laplace transforms of some frequently used functions to perform human reliability-related mathematical analysis in the area of power generation are presented in Table 2.1 [8, 9].

2.4.5 Definition V: Laplace Transform: Final-Value Theorem

If the following limits exist, then the final-value theorem may be expressed as follows:

$$\lim_{t\to\infty} f(t) = \lim_{s\to 0}[sf(s)] \tag{2.28}$$

Example 2.5 Prove with the aid of the equation presented below that the right side of Eq. (2.28) is equal to its left side.

$$f(t) = \frac{\mathrm{c}}{(\mathrm{c}+\mathrm{d})} - \frac{\mathrm{c}}{(\mathrm{c}+\mathrm{d})}e^{-(\mathrm{c}+\mathrm{d})t} \tag{2.29}$$

where c and d are constants.

With the aid of Table 2.1, we get the following Laplace transforms of Eq. (2.29)

$$f(s) = \frac{\mathrm{c}}{s(\mathrm{c}+\mathrm{d})} - \frac{\mathrm{c}}{(\mathrm{c}+\mathrm{d})}\cdot\frac{1}{(s+\mathrm{c}+\mathrm{d})}. \tag{2.30}$$

By inserting Eq. (2.30) into the right side of Eq. (2.28), we get

$$\lim_{s\to 0} s\left[\frac{\mathrm{c}}{s(\mathrm{c}+\mathrm{d})} - \frac{\mathrm{c}}{(\mathrm{c}+\mathrm{d})(s+\mathrm{c}+\mathrm{d})}\right] = \frac{\mathrm{c}}{(\mathrm{c}+\mathrm{d})}. \tag{2.31}$$

Table 2.1 Laplace transforms of some frequently used functions to perform human reliability-related mathematical analysis in the area of power generation

f(t)	f(s)
t^m, for $m = 0, 1, 2, 3, \ldots$	$m!/s^{m+1}$
c, a constant	c/s
e^{-bt}	$\frac{1}{s+b}$
$\frac{df(t)}{dt}$	$s\,f(s) - f(0)$
$\frac{tf(t)}{dt}$	$-\frac{df(s)}{ds}$
$\alpha_1 f_1(t) + \alpha_2 f_2(t)$	$\alpha_1 f_1(s) + \alpha_2 f_2(s)$
te^{-bt}	$1/(s+b)^2$

By substituting Eq. (2.29) into the left side of Eq. (2.28), we obtain

$$\lim_{t\to\infty}\left[\frac{c}{(c+d)} - \frac{c}{(c+d)}e^{-(c+d)t}\right] = \frac{c}{(c+d)}. \tag{2.32}$$

As the right sides of Eqs. (2.31) and (2.32) are exactly the same, it proves that the right side of Eq. (2.28) is equal to its left side.

2.5 Probability Distributions

Over the years, a large number of probability distributions have been developed to perform various types of statistical analysis [10]. This section presents some of these probability distributions considered useful to perform human reliability-related probability analysis in the area of power generation.

2.5.1 Exponential Distribution

This is probably the most widely used probability distribution to perform various types of reliability-related studies [11]. Its probability density function is defined by

$$f(t) = \theta e^{-\theta t} \quad \text{for } t \geq 0,\ \theta > 0 \tag{2.33}$$

where

$f(t)$ is the probability density function.
t is the time variable.
θ is the distribution parameter.

By inserting Eq. (2.33) into Eq. (2.22), we obtain the following expression for cumulative distribution function:

$$
\begin{aligned}
F(t) &= \int_0^t \theta e^{-\theta t} \mathrm{d}t \\
&= 1 - e^{-\theta t}.
\end{aligned} \tag{2.34}
$$

By substituting Eq. (2.33) in Eq. (2.25), we get the following expression for the distribution mean value:

$$
\begin{aligned}
m = E(t) &= \int_0^\infty t\theta e^{-\theta t} \mathrm{d}t \\
&= \frac{1}{\theta}
\end{aligned} \tag{2.35}
$$

where
m is the distribution mean value.

Example 2.6 Assume that in a power generating station, the human error rate is 0.08 errors per week. Calculate the probability of an error occurrence during a 30-week period with the aid of Eq. (2.34).

Thus, we have

$$
\begin{aligned}
t &= 30 \text{ weeks and} \\
\theta &= 0.08 \text{ errors/week.}
\end{aligned}
$$

By substituting the above data values in Eq. (2.34), we get

$$
\begin{aligned}
F(30) &= 1 - e^{-(0.08)(30)} \\
&= 0.9093.
\end{aligned}
$$

This means that there is 90.93 % chance for the occurrence of human error during the 30-week period.

2.5.2 Rayleigh Distribution

This distribution is named after John Rayleigh (1842–1919), its founder, and is frequently used in reliability work and in the theory of sound [1]. The probability density function of the distribution is defined by

$$f(t) = \frac{2}{\alpha^2} t e^{-\left(\frac{t}{\alpha}\right)^2} \quad \text{for } t \geq 0,\ \alpha > 0 \tag{2.36}$$

where

t is time.

α is the distribution parameter.

By substituting Eq. (2.36) into Eq. (2.22), we obtain the following equation for the cumulative distribution function:

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^2}. \tag{2.37}$$

With the aid of Eqs. (2.25) and (2.36), we obtain the following expression for the expected value of t:

$$E(t) = \alpha\Gamma(3/2) \tag{2.38}$$

where

$$\Gamma(y) = \int_0^\infty t^{y-1} e^{-t} \mathrm{d}t, \quad \text{for } y > 0. \tag{2.39}$$

2.5.3 Weibull Distribution

This distribution can be used to represent many different physical phenomena, and it is named after Weibull [12], a Swedish mechanical engineering professor, who developed it in the early 1950s. The probability density function of the distribution is defined by

$$f(t) = \frac{\beta t^{\beta-1}}{\theta^\beta} e^{-\left(\frac{t}{\theta}\right)^\beta} \quad t \geq 0,\ \beta > 0,\ \theta > 0 \tag{2.40}$$

where

t is time.

θ and β are the scale and shape parameters, respectively.

By substituting Eq (2.40) into Eq (2.22), we obtain the following equation for the cumulative distribution function:

$$F(t) = 1 - e^{-\left(\frac{t}{\theta}\right)^\beta}. \tag{2.41}$$

By inserting Eq. (2.40) into Eq. (2.25), we get the following equation for the expected value of t:

$$E(t) = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \tag{2.42}$$

where

$\Gamma(.)$ is the gamma function and is expressed by Eq. (2.39).

For $\beta = 2$ and 1, the Rayleigh and exponential distributions are the special cases of this distribution, respectively.

2.5.4 Bathtub Hazard Rate Curve Distribution

This probability distribution can be used to represent bathtub-shaped, decreasing and increasing, and increasing hazard/human error rates. It was developed in 1981 [13], and in the published literature, it is generally known as the Dhillon distribution/law/model [14–33].

The probability density function for the distribution is defined by [13].

$$f(t) = \beta\theta(\theta t)^{\beta-1} e^{-\left\{e^{(\theta t)^{\beta}} - (\theta t)^{\beta} - 1\right\}} \quad \text{for } \theta > 0,\ \beta > 0,\ t \geq 0 \tag{2.43}$$

where

t is time.

β and θ are the distribution shape and scale parameters, respectively.

By inserting Eq. (2.43) into Eq. (2.22), we get the following equation for the cumulative distribution function:

$$F(t) = 1 - e^{-\left\{e^{(\theta t)^{\beta}} - 1\right\}}. \tag{2.44}$$

At $\beta = 0.5$, this distribution gives the bathtub hazard rate curve, and at $\beta = 1$, it becomes the extreme value distribution. In other words, the extreme value distribution is the special case of this distribution at $\beta = 1$.

2.6 Solving First-Order Differential Equations with Laplace Transforms

Laplace transforms are an effective tool to find solution to linear first-order differential equations, and in human reliability-related studies, time-to-time linear first-order differential equations are solved. The application of Laplace transforms to find solution to a set of first-order differential equations describing the reliability of maintenance personnel in a power plant is demonstrated through the following example:

Example 2.7 Assume that the reliability of maintenance personnel in a power plant with respect to human error is described by the following two linear first-order differential equations:

$$\frac{\mathrm{d}P_n(t)}{\mathrm{d}t} + \theta_m P_n(t) = 0 \tag{2.45}$$

$$\frac{\mathrm{d}P_e(t)}{\mathrm{d}t} - \theta_m P_n(t) = 0 \tag{2.46}$$

where

$P_n(t)$ is the probability that the maintenance personnel are performing their tasks normally at time t.

$P_e(t)$ is the probability that the maintenance personnel have committed an error at time t.

θ_m is the constant error rate of the maintenance personnel.

At time $t = 0,\ P_n(0) = 1,$ and $P_e(0) = 0$.

Find solutions to Eqs. (2.45) and (2.46) with the aid of Laplace transforms.

By taking the Laplace transforms of Eqs. (2.45) and (2.46) and then using the given initial conditions, we get

$$P_n(s) = \frac{1}{s + \theta_m} \tag{2.47}$$

$$P_e(s) = \frac{\theta_m}{s(s + \theta_m)} \tag{2.48}$$

where

s is the Laplace transform variable.

Taking the inverse Laplace transforms of Eqs. (2.47) and (2.48), we obtain

$$P_n(t) = e^{-\theta_m t} \tag{2.49}$$

$$P_e(t) = 1 - e^{-\theta_m t}. \tag{2.50}$$

Thus, Eqs. (2.49) and (2.50) are the solutions to Eqs. (2.45) and (2.46).

2.7 Problems

1. Write an essay on the history of mathematics.
2. Describe the following three laws:
   - Idempotent law.
   - Absorption law.
   - Distributive law.

3. What is the difference between mutually exclusive and independent events?
4. Discuss the basic properties of probability.
5. Define the following:
   - Cumulative distribution function.
   - Expected value.
6. Prove that the right-hand side of Eq. (2.10) is equal to its left-hand side.
7. Write down the probability density function for Rayleigh distribution.
8. What are the special case probability distributions of the Weibull distribution?
9. Using Eq. (2.27), obtain Laplace transform of the following function:

$$f(t) = 1 - e^{-\mu t} \tag{2.51}$$

   where
   t is a variable.
   μ is a constant.
10. Prove Eq. (2.44) using Eqs. (2.22) and (2.43).

References

1. Eves H (1976) An introduction to the history of mathematics. Holt, Rinehart, and Winston, New York
2. Owen DB (ed) (1976) On the history of statistics and probability. Marcel Dekker, New York
3. Lipschutz S (1964) Set theory and related topics. McGraw Hill Book Company, New York
4. Lipschutz S (1965) Probability. McGraw Hill Book Company, New York
5. Fault Tree Handbook (1981) Report No. NUREG-0492, U.S. Nuclear Regulatory Commission, Washington, D.C.
6. Mann NR, Schafer RE, Singpurwalla ND (1974) Methods for statistical analysis of reliability and life data. Wiley, New York
7. Shooman ML (1968) Probabilistic reliability: an engineering approach. McGraw-Hill Book Company, New York
8. Spiegel MR (1965) Laplace transforms. McGraw Hill Book Company, New York
9. Oberhettinger F, Baddii L (1973) Tables of Laplace transforms. Springer, New York
10. Patel JK, Kapadia CH, Owen DB (1976) Handbook of statistical distributions. Marcel Dekker, New York
11. Davis DJ (1952) An analysis of some failure data. J Am Stat Assoc 113–150
12. Weibull W (1951) A statistical distribution function of wide applicability. J Appl Mech 18:293–297
13. Dhillon BS (1981) Life distributions. IEEE Trans Reliab 30(5):457–460
14. Baker AD (1993) A nonparametric estimation of the renewal function. Comput Oper Res 20(2):167–178
15. Cabana A, Cabana EM (2005) Goodness-of-fit to the exponential distribution, focused on Weibull alternatives. Commun Stat Simul Comput 34:711–723
16. Grane A, Fortiana J (2011) A directional test of exponentiality based on maximum correlations. Metrika 73:255–274
17. Henze N, Meintnis SG (2005) Recent and classical tests for exponentiality: a partial review with comparisons. Metrika 61:29–45

18. Hollander M, Laird G, Song KS (2003) Nonparametric interference for the proportionality function in the random censorship model. Nonparametric Stat 15(2):151–169
19. Jammalamadaka SR, Taufer E (2003) Testing exponentiality by comparing the empirical distribution function of the normalized spacings with that of the original data. J Nonparametric Stat 15(6):719–729
20. Jammalamadaka SR, Taufer E (2006) Use of mean residual life in testing departures from exponentiality. J Nonparametric Stat 18(3):277–292
21. Kunitz H (1989) A new class of bathtub-shaped hazard rates and its application in comparison of two test-statistics. IEEE Trans Reliab 38(3):351–354
22. Kunitz H, Pamme H (1993) The mixed gamma ageing model in life data analysis. Stat Pap 34:303–318
23. Meintanis SG (2009) A class of tests for exponentiality based on a continuum of moment conditions. Kybernetika 45(6):946–959
24. Morris K, Szynal D (2008) Some U-statistics in goodness-of-fit tests derived from characterizations via record values. Int J Pure Appl Math 46(4):339–414
25. Morris K, Szynal D (2007) Goodness-of-fit tests based on characterizations involving moments of order statistics. Int J Pure Appl Math 38(1):83–121
26. Na MH (1999) Spline hazard rate estimation using censored data. J KSIAM 3(2):99–106
27. Nam KH, Chang SJ (2006) Approximation of the renewal function for Hjorth model and Dhillon model. J Korean Soc Qual Manage 34(1):34–39
28. Nam KH, Park DH (1997) Failure rate for Dhillon model. In: Proceedings of the spring conference of the Korean society, pp 114–118
29. Nimoto N, Zitikis R (2008) The Atkinson index, the moran statistic, and testing exponentiality. J Jpn Stat Soc 38(2):187–205
30. Noughabi HA, Arghami NR (2011) Testing exponentiality based on characterizations of the exponential distribution. J Stat Comput Simul i First:1–11
31. Szynal D (2010) Goodness-of-fit tests derived from characterizations of continuous distributions, stability in probability, Banach Center Publications, vol 90. Institute of Mathematics, Polish Academy of Sciences, Warszawa, pp 203–223
32. Szynal D, Wolynski W (2012) Goodness-of-fit tests for exponentiality and Rayleigh distribution. Int J Pure Appl Math 78(5):751–772
33. Na MH, Lee HW, Kim JJ (1997) A smooth estimation of failure rate function. J Korean Soc Qual Manage 25(3):51–61

Chapter 3
Basic Human Factors, Reliability, and Error Concepts

3.1 Introduction

Over the years, many new developments have taken place in the areas of human factors, reliability, and error as humans play a key role in the overall reliability of engineering systems. In fact, human factors, reliability, and error have become recognizable disciplines in industry in many parts of the world. There are many standard documents concerning human factors that also, directly or indirectly, cover human reliability and error. Often, such standard documents are cited in the design specification of complex engineering systems [1, 2].

More specifically, the requirements specified in these documents must be satisfied by the new system design. Needless to say, during the design and development of power generation systems, particularly in the area of nuclear power generation, nowadays, it is common to come across human factors specialists (who cover human reliability and error as well) working alongside design engineers. These specialists, in order to produce effective power generation systems with respect to humans, make use of various human factors, reliability, and error concepts [3, 4].

This chapter presents various useful basic human factors, reliability, and error concepts for application in the area of power generation.

3.2 Human Factors Objectives, Human and Machine Characteristics Comparisons, and Types of Man–Machine Systems

There are many objectives of human factors. They may be grouped under the following four categories [5]:

- **Category I Objectives: Fundamental Operational Objectives**. These are concerned with increasing safety, reducing human errors, and improving system performance.

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_3,

- **Category II Objectives: Objectives Affecting Reliability and Maintainability**. These are concerned with improving maintainability, reducing the need for manpower, increasing reliability, and reducing training requirements.
- **Category III Objectives: Objectives Affecting Operators and Users**. These are concerned with improving ease of use and user acceptance, improving aesthetic appearance, improving the work environment, and reducing fatigue, physical stress, boredom, and monotony.
- **Category IV Objectives: Miscellaneous Objectives**. These are concerned with items such as lowering losses of time and equipment and improving production economy.

Humans and machines possess many characteristics that can be compared. Thus, some of the important comparable human and machine characteristics are presented in Table 3.1 [6, 7].

Although there are many different types of man–machine systems, they may be grouped under three types as shown in Fig. 3.1 [8].

The automated systems perform operation-related functions such as processing, decision making, action, and sensing. Most of these systems are of the closed-loop type (a closed-loop system may be expressed as a continuous system performing some processes that need continuous control and feedback for its successful operational mission) and usually the basic functions associated with such systems are programming, maintenance, and monitoring.

The manual systems are made up of hand tools and other aids along with the operator who controls the overall operation. The operator makes use of his/her own physical energy as a power source, and then transmits/receives from the tools a great amount of information.

Finally, the mechanical or semi-automatic systems are made up of well integrated parts, such as various types of powered machine tools. Usually, in these systems, the machines provide the power and the human operators typically perform the control-related functions.

3.3 Typical Human Behaviours and Their Corresponding Design Considerations

Over the years, the researchers working in the area of human factors have observed various human behaviours. Some of the typical human behaviours and their corresponding design considerations in the parentheses are as follows [3]:

- Humans will often use their sense of touch to test or explore the unknown (pay special attention to this factor during the design process, particularly to the product handling aspect).
- Humans get easily confused with unfamiliar items (avoid designing totally unfamiliar items).

Table 3.1 Human and machine characteristics comparisons

No.	Human	Machine
1	Humans possess inductive capabilities	Machines possess poor inductive capability, but a good deductive ability
2	Humans’ memory could be constrained by elapsed time, but it has no capacity limitation problem	Machines’ memory is not influenced by absolute and elapsed times
3	Humans are subject to fatigue that increases with the number of hours worked and lowers with rest	Machines are free from fatigue, but require periodic maintenance
4	Humans require some degree of motivation	Machines require no motivation at all
5	Humans are affected by environmental factors such as temperature, noise, and hazardous materials; and they need air to breathe	Machines are not easily affected by the environment, thus they are useful for application in unfriendly environments
6	Humans’ consistency can be low	Machines are consistent, unless there are failures
7	Humans may be absent from work due to factors such as strikes, illness, personal matters, and training	Machines are subject to malfunctions or failures
8	Humans possess a high degree of intelligence and are capable to apply judgements to solve unexpected problems	Machines possess limited intelligence and judgemental capability
9	Humans’ reaction time is rather slow in comparison to that of machines	Machines have a fast reaction time to external signals

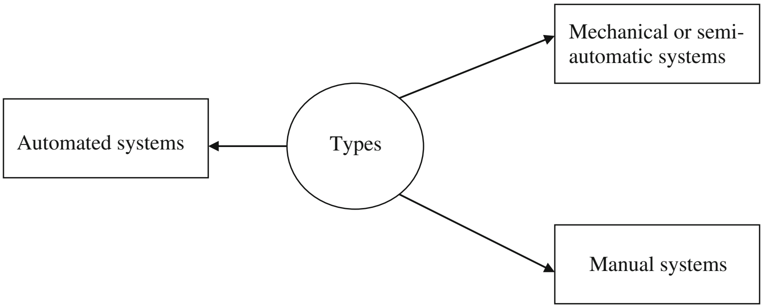

Fig. 3.1 Types of man–machine systems

- Humans frequently tend to hurry (develop design so that it clearly takes into consideration the human hurry element).
- Humans frequently regard manufactured products as being safe (design products so that they become impossible to be used incorrectly).
- Humans have become accustomed to certain colour meanings (during the design process strictly observe existing colour-coding standards).
- Humans generally possess very little knowledge regarding their physical shortcomings (develop proper design by taking into consideration the basic characteristics and shortcomings of humans).
- Humans always expect that faucets/valve handles will rotate counter-clockwise for increasing the flow of steam, liquid, or gas (design such items according to the expectations of humans).
- Humans generally expect to turn on the electrical power, the switches have to move upward, or to the right, etc. (design such switches according to the expectations of the humans).

3.4 Human-Sensory Capacities

As humans possess many useful sensors (i.e., touch, smell, hearing, sight, and taste), a clear understanding of their sensory capacities can be very helpful to reduce the occurrence of human errors in the area of power generation. Thus, four human-sensory capacities are described below, separately [4, 9].

3.4.1 Noise

Noise may simply be described as sounds that lack coherence and reactions of humans to noise extend beyond the auditory systems (i.e., to feelings such as fatigue, boredom, well-being, or irritability). Furthermore, excessive noise can lead to various types of problems including adverse effects on tasks requiring a high degree of muscular coordination and precision or intense concentration, loss of hearing if exposed for long periods, and reduction in the efficiency of workers.

Generally, two major physical characteristics (i.e., frequency and intensity) are used in describing noise. In the case of frequency, the human ears are most sensitive to frequencies in the range of 600–900 Hz and they have the capacity to detect sounds of frequencies from 20 to 20,000 Hz. As per the past experiences [9, 10], humans can suffer a major loss of hearing, if they are exposed to noise frequencies between 4,000 and 6,000 Hz for a long period of time.

In the case of intensity, it is usually measured in decibels (dB) and a person exposed to over 80 dB of noise can experience permanent or temporary loss of hearing. It is to be noted that intensity levels for noise sources such as heavy traffic, normal conversation, household ventilation fan, quiet residential area, voice whisper, and motion picture sound studio are 70, 60, 56, 40, 20, and 10 dB, respectively [8, 10].

3.4.2 Touch

The sense of touch is related to the ability of humans in interpreting auditory and visual stimuli. The sensory cues received by the skin and muscles can be used to send messages to the brain, thus relieving the ears and the eyes a part of the workload. In situations when human users are expected to rely completely on their touch sensors, different types of knob shapes can be adopted for potential applications.

It is to be added that the application of the touch sensor in technical tasks is not new; in fact, it has been used by craft workers quite successfully for centuries to detect surface roughness and irregularities in their work. Nonetheless, various studies performed over the years clearly indicate that the detection accuracy of surface irregularities improves dramatically when a person moves an intermediate thin cloth or a piece of paper over the object surface instead of using bare fingers [11].

3.4.3 Vibration

Various studies conducted over the years clearly indicate that the existence of vibration could be detrimental to the performance of both mental and physical tasks by humans such as operation and maintenance personnel in the area of power generation. There are many parameters of vibrations including acceleration, frequency, velocity, and amplitude. In particular, low frequency and large amplitude vibrations contribute to various problems including motion sickness, headaches, fatigue, eyestrain, and interference with one's ability to read and interpret instruments effectively [9]. Symptoms such as these become less pronounced as the vibration amplitude decreases and the frequency increases. Nonetheless, it is to be noted that low amplitude and high frequency vibration can also cause fatigue to a certain degree.

Some of the useful guidelines to reduce vibration and motion effects are presented below [9, 12].

- Resist shocks and vibrations through proper designs or isolate them using springs, cushioned mountings, shock absorbers, etc.
- Aim to eliminate vibrations in excess of 0.08 mil amplitude.
- Use cushioned seats or damping materials to lower vibrations transmitted to a seated person and avoid vibrations of frequencies 3–4 Hz as this is a vertically seated person's resonant frequency.

3.4.4 Sight

This is stimulated by the electromagnetic radiation of certain wavelengths, generally known as the visible portion of the electromagnetic spectrum. The areas of the spectrum, as seen by the human eyes appear to vary in brightness. For example, during the day, the eyes of humans are most sensitive to greenish-yellow light with a wavelength of about 5,500 Å [9].

Furthermore, the human eyes perceive all colours when they are looking straight ahead but as the viewing angle increases, the colour perception begins to decrease. In addition, the eyes of humans see differently from different angles. Some of the additional factors concerned with colour are presented below [9].

- Colour differences are very minimal at night or in poorly illuminated places. In particular, for a small point source (e.g., a small warning light) or from a distant, it is quite impossible to make a distinction between blue, green, yellow, and orange. In fact, all of them will appear to be white.
- Staring at a specific coloured light and then glancing away may result in the reversal of colour in the brain. For example, to stare at a red or green light and then glance away, the signal to the brain may completely reverse the colour.
- Colour-weak individuals do not see colours in a similar way as normal people do.

Three sight-related useful guidelines are as follows:

- Aim to use red filters with wavelengths greater than 6,500 Å.
- Avoid relying too much on colour when critical activities may be carried out by fatigues persons.
- Select the proper colour so that colour-weak individuals do not get confused.

3.5 Useful Human Factors Formulas

Over the years, researchers working in the area of human factors have developed various types of mathematical formulas to estimate human factors-related information. Some of these formulas considered useful for application in the area of power generation are presented below.

3.5.1 Formula for Estimating Character Height

This formula is concerned with estimating the character height by considering factors such as viewing distance, the importance of reading accuracy, viewing conditions, and illumination. Thus, the character height is expressed by [13]

$$CH = \alpha \, VD + CFI + CFVI \tag{3.1}$$

where

CH is the correction height in inches.

α is a constant with the specified value of 0.0022.

CFVI is the correction factor for viewing and illumination conditions. Its recommended values are as follows: 0.26 (below a 1 foot-candle and unfavourable reading conditions), 0.16 (below a 1 foot-candle and favourable reading conditions), 0.16 (above a 1 foot-candle and unfavourable reading conditions), and 0.06 (above a 1 foot-candle and favourable reading conditions).

CFI is the correction factor for importance. Its recommended values for similar items or emergency labels is 0.075 and for other items CFI $= 0$.

VD is the viewing distance expressed in inches.

Example 3.1 In a power generating station's control room, the estimated viewing distance of an instrument panel is 40 inches and after a careful consideration, the values of CFVI and CFI were decided to be 0.06 and 0.075, respectively. Calculate the height of the label characters to be used at the instrument panel.

By substituting the given data values into Eq. (3.1), we obtain

$$\begin{aligned} CH &= (0.0022)(40) \; + \; 0.075 + 0.06 \\ &= \; 0.223 \;\; \text{inch} \end{aligned}$$

Thus, the label characters' height to be used is 0.223 inch.

3.5.2 Formula for Estimating Rest Period

Past experience clearly indicates that the incorporation of appropriate rest periods is essential, when humans perform lengthy or strenuous tasks. Thus, this formula is concerned with determining the length of unscheduled or scheduled required rest periods.

The length of the required rest period is expressed by [14]

$$\text{RLRP} = \frac{\text{WT}(\text{AEC} - \text{SE})}{(\text{AEC} - \text{ARL})} \tag{3.2}$$

where

RLRP is the required length of the rest period expressed in minutes.
AEC is the average energy cost/expenditure expressed in kilocalories per minute of work.
SE is the kilocalories per minute adopted as standard.
ARL is the approximate resting level expressed in kilocalories per minute. Usually, the value of ARL is taken as 1.5.
WT is the working time expressed in minutes.

It is to be noted that the average energy expenditure in kilocalories per minute (i.e., SE) and the human heart rate in beats per minute (in parentheses) for tasks such as packing on conveyors, cleaning tables and floors, and unloading coal cars in power generation plants are 3.7 (113), 4.5 (112), and 8 (150), respectively.

Example 3.2 Assume that a worker is performing a certain task at a power generation plant for 120 min and his/her average energy expenditure is 9 kcal/min. Calculate the length of the required rest period if SC = 8 kcal/min and ARL = 1.5 kcal/min.

By inserting the specified data values into Eq. (3.2), we get

$$\begin{aligned} \text{RLRP} &= \frac{120(9 - 8)}{(9 - 1.5)} \\ &= 16 \text{ min} \end{aligned}$$

Thus, the length of the required rest period is 16 min.

3.5.3 Formula for Estimating Glare Constant

Past experience over the years, clearly indicates that various types of human errors can occur in the area of power generation due to glare. Thus, this formula is concerned with estimating the value of the glare constant. The glare constant is expressed by [14]

$$\theta = \frac{\left(\alpha^{0.8}\right)\left(\gamma^{1.6}\right)}{A^2(\mathrm{GBL})} \tag{3.3}$$

where

- θ is the glare constant.
- A is the angle between the direction of the glare source and the viewing distance.
- GBL is the general background luminance.
- α is the solid angle subtended at the eye by the source.
- γ is the source luminance.

3.5.4 Formula for Estimating Human Energy Cost Associated with Lifting Weights

As tasks such as lifting weights cost human energy, this formula is concerned with estimating human energy cost (EC) associated with lifting weights. The EC, is kilocalories per hour, is expressed by [15].

$$\mathrm{EC} = \frac{(\mathrm{LH})(n)(w)(\mu)}{1{,}000} \tag{3.4}$$

where

- LH is the lifting height in feet.
- n is the number of lifts per hour.
- w is the weight to be lifted in pounds.
- μ is the cost of energy per lift (gcal/ft.lb).

Example 3.3 Assume that we have the following data values:

- LH = 3 ft
- $n = 30$ lifts/h
- $w = 10$ lb
- $\mu = 5$ gcal/ft.lb

Calculate the hourly EC.

By substituting the given data values into Eq. (3.4), we get

$$\begin{aligned} \mathrm{EC} &= \frac{(3)(30)(10)(5)}{1{,}000} \\ &= 4.5 \text{ kcal/h} \end{aligned}$$

Thus, the hourly EC is 4.5 kcal/h.

Table 3.2 A sample of questions to be addressed to incorporate human factors into the designs of engineering systems

Question no.	Question
1	• Were the human factor principles considered clearly in the workspace design?
2	• Were all controls designed by taking into consideration factors such as accessibility, size, and shape?
3	• Were environmental factors such as noise, illumination, and temperature considered in regard to satisfactory levels of human performance?
4	• Is it simple and straightforward to identify each control device?
5	• Are all the displays compatible with their corresponding control devices with respect to human factors?
6	• Was proper attention given to training and complementing work-related aids?
7	• What type of sensory channels would be the most suitable for messages to be delivered through the displays?
8	• Were visual display arrangements optimized?
9	• Were human decision making and adaptive capabilities used properly in the design?

3.6 Human Factors Checklist, Guidelines, and Data Collection Sources

Over the years, professionals working in the area of human factors have developed a checklists of questions to be addressed for incorporating human factors into the designs of engineering systems. These questions can easily be tailored to suit specific engineering systems' designs under consideration. Some examples of such questions are presented in Table 3.2 [6].

Some of the general human factors' guidelines considered useful for application in power generation systems' designs are as follows [3, 7]:

- Make use of services of human factors specialists as considered appropriate.
- Review system/product objectives in regard to human factors.
- Review all final production drawings with respect to human factors.
- Develop an effective human factors checklist for application during system/product design and production phases.
- Use mock-ups to "test" the effectiveness of user–hardware interface designs.
- Obtain appropriate human factors-related design guide and reference documents.
- Perform appropriate field test of the system/product design prior to its approval for delivery to customer.

There are many sources from which human factors-related data can be collected. Some of the important ones are shown in Fig. 3.2 [6, 13].

The test reports contain data obtained from testing manufactured goods. The published standards are the documents developed by organizations such as

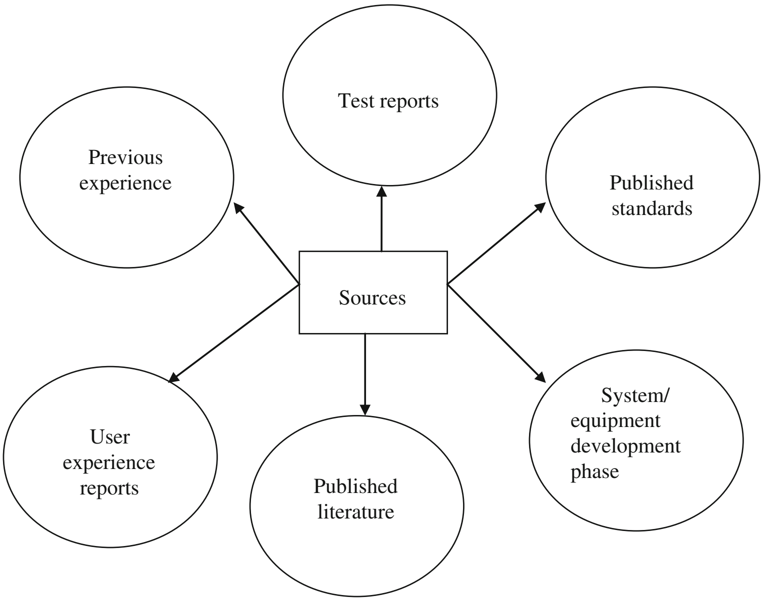

Fig. 3.2 Sources for collecting human factors-related data

professional societies and government agencies, and they are considered a good source for obtaining human factors-related data. The previous experience is a good source to obtain data from similar cases that have occurred in the past.

The user experience reports contain data-reflecting users' experiences with system/equipment in the field-use environment. The published literature is another good source to obtain human factors-related data, and it includes items such books, conference proceedings, and journals. Finally, various types of human factors-related data can also be obtained during the system/equipment development phase.

3.7 Operator Stress Characteristics, Occupational Stressors, and General Stress Factors

In order to operate engineering systems, human operators perform various types of tasks and in performing such tasks, they may have certain limitations or shortcomings. The probability of human error occurrence increases quite significantly when these limitations are violated. During the system design process, a careful consideration to operator characteristics or limitations can reduce the probability of human error occurrence quite significantly. Some of these characteristics are presented below [16]:

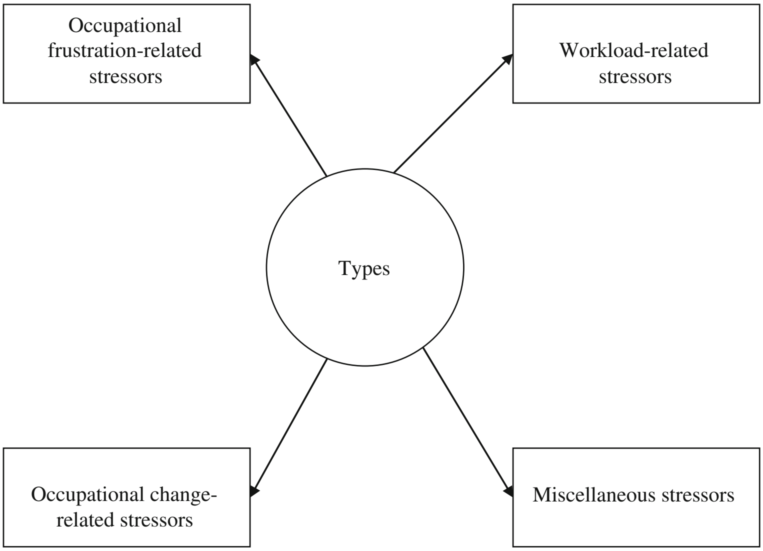

Fig. 3.3 Types of occupational stressors

- Requirements for making decisions on the basis of data obtained from diverse sources.
- Performing task steps at quite high speed.
- Requirements for making quick comparisons of two or more displays.
- Having short decision-making time.
- Requirements for operating more than one control simultaneously at high speed.
- Poor feedback information to determine whether the actions taken were correct or not.
- Performing tasks that need a fairly long sequence of steps.
- The requirements or prolonged monitoring.

Past experiences, over the years, clearly indicate that stress plays an important role in the reliability of a person performing a certain task. There are basically four types of occupational stressors as shown in Fig. 3.3 [4, 17].

The occupational frustration-related stressors are concerned with the problems related to occupational frustration. This frustration is generated in conditions when the job inhibits the meeting of specified goals. The factors that form elements of occupational frustration include ineffective career development guidance, bureaucracy difficulties, and lack of effective communication.

The occupational change-related stressors are concerned with the occupational change that disrupts cognitive, behavioural, and physiological patterns of functioning of the person. Some examples of the occupational change are organizational restructuring, relocation, and promotion. The workload-related stressors are concerned with the problems related to work underload or work overload. In the case of work underload, the work activities being carried out by the individual fail to provide appropriate stimulation. Some examples of the work underload are lack of opportunities to use acquired skills and expertise of an individual, lack of any intellectual input, and repetitive performance. In contrast, in the case of work overload, job requirements exceed the ability of the individual to satisfy them effectively.

Finally, the miscellaneous stressors are concerned with those stressors that are not incorporated into the above three categories or types. Some examples of these stressors are too little or too much lighting, too much noise, and poor interpersonal relationships.

Various studies conducted, over the years in the area of human factors, have clearly indicated that there are many general factors that significantly increase stress on a person, in turn resulting in a considerable deterioration in his/her reliability. Some of these general factors are as follows [2, 18]:

- Low chances for promotion.
- Serious finance-related difficulties.
- Poor health.
- Lacking the necessary expertise to carry out the ongoing job.
- Having difficulties with children or spouse or both.
- Possibility of redundancy at work.
- Rather excessive demands at work from superiors.
- Having to work with people with unpredictable temperaments.

3.8 Human Performance Reliability Function

In the area of engineering, humans perform time-continuous tasks such as scope monitoring, missile countdown, and aircraft manoeuvring. In such situations, human performance reliability parameter plays a crucial role. The general human performance reliability function for time-continuous tasks can be developed the same way as the development of the general reliability function for hardware engineering systems/items. Thus, using Ref. [19], we write

$$e_{\mathrm{h}}(t) = -\frac{\mathrm{d}R_{\mathrm{h}}(t)}{\mathrm{d}t} \cdot \frac{1}{R_{\mathrm{h}}(t)} \tag{3.5}$$

where

$R_{\mathrm{h}}(t)$ is the human performance reliability at time t
$e_{\mathrm{h}}(t)$ is the time t dependent human error rate

By rearranging Eq. (3.5), we obtain

$$\frac{\mathrm{d}R_{\mathrm{h}}(t)}{R_{\mathrm{h}}(t)} = -e_{\mathrm{h}}(t)\mathrm{d}t \tag{3.6}$$

Integrating both sides of Eq. (3.6) over the time interval $[0, t]$, we obtain

$$\int_0^t \frac{1}{R_h(t)} \cdot dR_h(t) = -\int_0^t e_h(t)dt \quad (3.7)$$

Since at $t = 0$, $R_h(t) = 1$, we rewrite Eq. (3.7) to the following form:

$$\int_1^{R_h(t)} \frac{1}{R_h(t)} \cdot dR_h(t) = -\int_0^t e_h(t)dt \quad (3.8)$$

After evaluating the left side of Eq. (3.8), we obtain

$$\ln R_h(t) = -\int_0^t e_h(t)dt \quad (3.9)$$

Using Eq. (3.9), we obtain the following expression for human performance reliability:

$$R_h(t) = e^{-\int_0^t e_h(t)dt} \quad (3.10)$$

Equation (3.10) is the general expression for human performance reliability, and it can be used to calculate human performance reliability for any time to human error statistical distribution including exponential, gamma, and Weibull.

Example 3.4 Assume that the times to human error of a power generation system operator follow Weibull distribution. Thus, his/her time-dependent error rate is defined by

$$e_h(t) = \frac{\mu}{\gamma}\left(\frac{t}{\gamma}\right)^{\mu-1} \quad (3.11)$$

where
μ is the shape parameter.
γ is the scale parameter.
t is time.

Obtain the following:

- An expression for the performance reliability function of the power generation system operator.
- Reliability of the power generation system operator for a 8-hour mission, if $\mu = 1$ and $\gamma = 200$ h.

By inserting Eq. (3.11) into Eq. (3.10), we obtain

$$\begin{aligned} R_{\mathrm{h}}(t) &= e^{-\int_0^t \frac{\mu}{\gamma}\left(\frac{t}{\gamma}\right)^{\mu-1} \mathrm{d}t} \\ &= \exp\left[-\left(\frac{t}{\gamma}\right)^{\mu}\right] \end{aligned} \tag{3.12}$$

By substituting the specified data values into Eq. (3.12), we get

$$\begin{aligned} R_{\mathrm{h}}(8) &= \exp\left[-\left(\frac{8}{200}\right)\right] \\ &= 0.9607 \end{aligned}$$

Thus, the expression for the performance reliability function of the power generation system operator is given by Eq. (3.12) and his/her reliability for an 8-hour mission is 0.9607.

3.9 Human Error Occurrence Reasons, Common Ways, Consequences, and Human Error Classifications

There are many reasons for the occurrence of human errors. Some of the important ones are shown in Fig. 3.4 [4, 20].

There are many ways for the occurrence of human error. The common ones are as follows [21]:

- Making an incorrect decision in response to a problem.
- Poor timing and inadequate response to a contingency.
- Failure to carry out a required function.
- Failure to recognize a hazardous situation.
- Performing a task that should not have been executed.

There are various consequences for the occurrence of human errors. They may vary from one piece of equipment to another, from one situation to another, or from one task to another. Furthermore, a consequence can range from minor to severe, for example, from a short delay in system performance to a major loss of lives and property. Nonetheless, in regard to equipment, the consequences of human errors may be grouped under the following three classifications:

- Delay in equipment operation is insignificant.
- Equipment operation is delayed significant but not stopped.
- Equipment operation is stopped completely.

Human errors may be grouped under many classifications. The seven commonly used classifications are shown in Fig. 3.5 [20, 22].

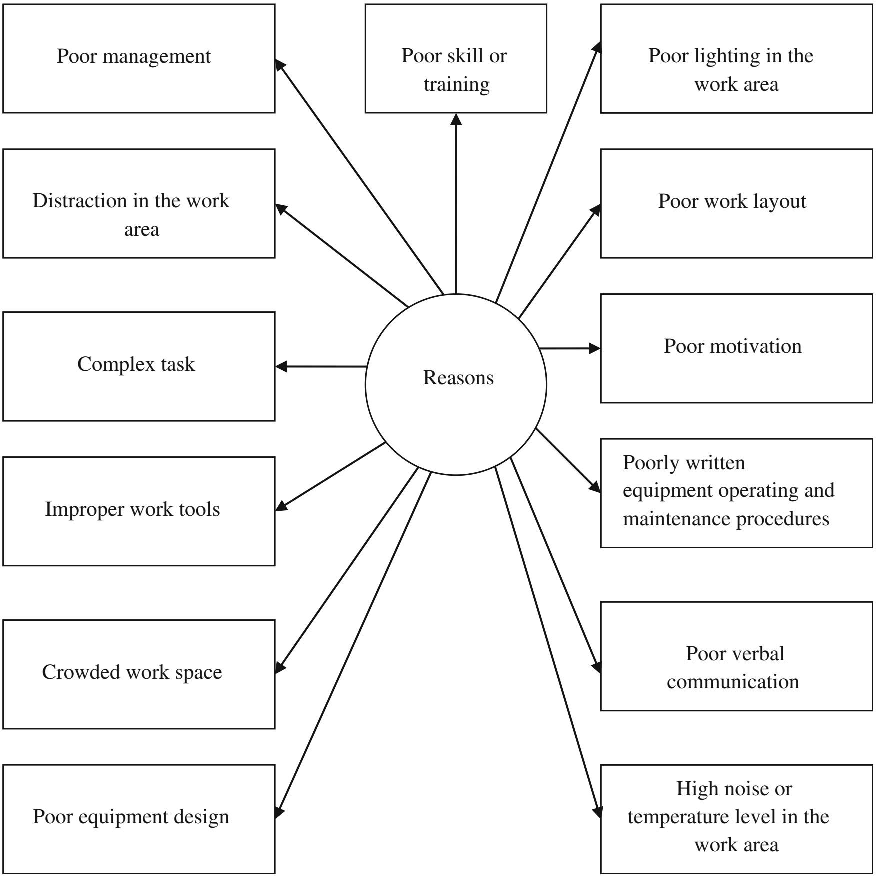

Fig. 3.4 Reasons for the occurrence of human errors

The operator errors occur in the field-use environment of equipment due to operating personnel, when these personnel overlook to follow correct procedures, or there is lack of proper procedures. More specifically, the factors that can lead to operator errors include poor training, task complexity, poor environmental conditions, and operator carelessness. The design errors occur due to poor design and the types of design errors are failure to ensure the effectiveness of the man and machine interactions, failure to implement human-related needs in the design, and assigning inappropriate functions to humans. An example of a design error is the placement of displays and controls so much apart that operating personnel find quite difficult to use both of them in an effective manner.

The fabrication errors occur during the product assembly process due to poor workmanship. Some examples of these errors are incorrect soldering, using a

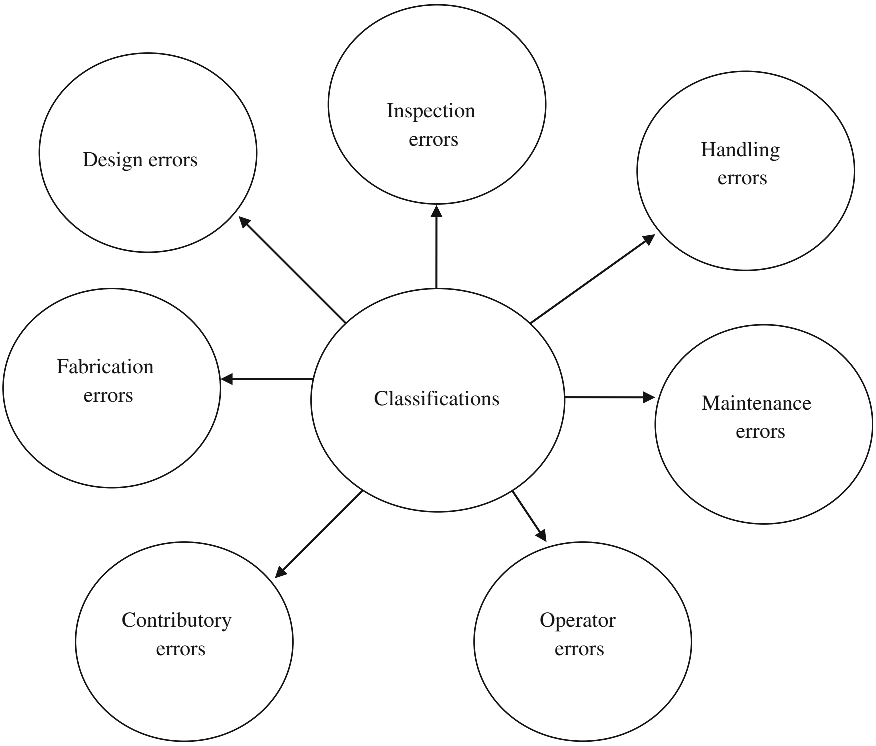

Fig. 3.5 Classifications of human errors

wrong part, assembly incompatible with blueprints, and omitting a component. Some of the reasons for the occurrence of fabrication errors are poor illumination, excessive temperature, excessive noise level, and poor blueprints [22]. The maintenance errors occur generally during the field-use environment of equipment/item due to incorrect installation or repair. Two examples of maintenance errors are the use of incorrect grease at appropriate points of the equipment/item and wrong calibration of equipment/item.

The handling errors occur due to poor storage or transport facilities that are not in accordance with the recommendations of equipment/item manufacturer. The inspection errors are associated with accepting out-of-tolerance items or rejecting in-tolerance items. As per Ref. [23], according to various studies, the inspection effectiveness average is about 85 %.

Finally, the contributory errors are the ones that are quite difficult to define either human or related to equipment.

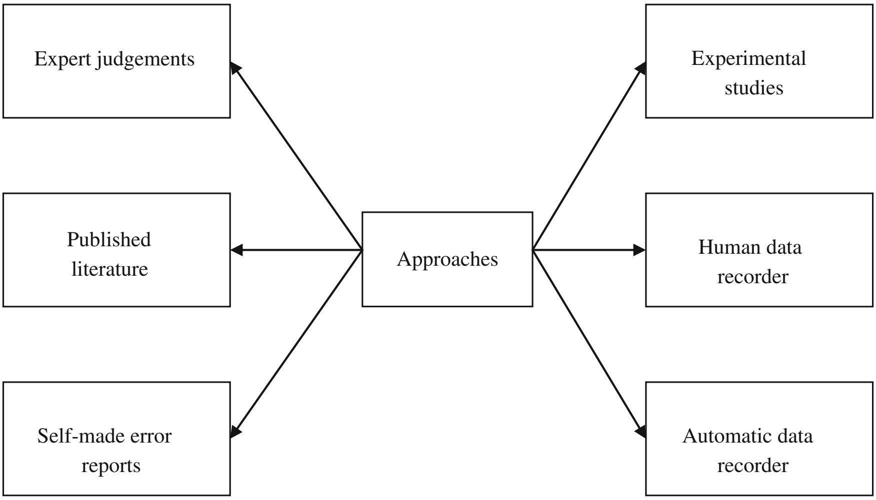

Fig. 3.6 Approaches for collecting human reliability and error data

3.10 Human Reliability and Error Data Collection Sources and Quantitative Data Values

Human reliability and error data are the backbone of any human reliability-related prediction. These data can be collected through means such as shown in Fig. 3.6 [4, 24–26].

The expert judgements approach is frequently used by human reliability methodologists to obtain human reliability-related data, and it has the following two attractive features:

- It is relatively easy to develop because a large amount of data can be collected from a small number of expert respondents.
- It is comparatively cheaper to develop.

In contrast, the two main drawbacks of this approach are frequent use of less experienced experts than required and less reliable than data collected through other means or approaches. The data collected from experimental studies is normally generated under the laboratory conditions. These conditions may not be the actual representative of the real life conditions. Furthermore, the approach is expensive and time-consuming. Nonetheless, the main advantage of data collected through the experimental studies approach is that the data are probably the least influenced by the subjective elements that may induce some error. An example of data based on the findings of experimental studies is the Data Store [27].

The automatic data recorder approach makes use of instrumentation that permits the automatic recording of operator actions. An example is the operational

Table 3.3 Human reliability and error data for selective tasks

No.	Error/task description	Errors per plant month (boiling water reactors)	Errors per million operations	Performance reliability
1	Wrong servicing	0.03	–	–
2	Requirement misunderstanding/ misinterpretation	0.0074	–	–
3	Adjusting incorrectly	0.026	–	–
4	Closing valve incorrectly	–	1,800	–
5	Reading gauge incorrectly	–	5,000	–
6	Turning rotary selector switch to certain position	–	–	0.9996
7	Finding maintenance (scheduled) approaches in maintenance manual	–	–	0.997

performance recording and evaluation data system (OPREDS) [28]. The human data recorder approach calls for the physical presence of a person for observing task performance and documenting events as necessary. The drawbacks of this approach include costly and the observer may overlook to recognize committed errors.

The published literature approach is concerned with collecting data from publications such as books, journals, and conference proceedings. Finally, in the case of self-made error reports' approach, the individual who makes the error also reports that error. The main drawback of this approach is that humans are generally quite reluctant to admit making an error.

Some of the specific data banks for collecting human reliability-related data are as follows:

- Nuclear Plant Reliability Data System [29].
- Safety-Related Operator Action (SROA) Program [30].
- Technique for Establishing Personnel Performance Standards (TEPPS) [30].
- Aerojet General Method [31].
- Operational Performance Recording and Evaluation Data System (OPREDS) [28].
- Data Store [27].
- Aviation Safety Reporting System [32].

Human reliability and error data for selective tasks taken from published sources, directly or indirectly related to power generation systems, are presented in Table 3.3 [4].

3.11 Problems

1. Compare human and machine characteristics.
2. List at least eight typical human behaviours.
3. Discuss the following two human-sensory capacities:
   - Noise.
   - Touch.
4. Write down the formula that can be used to estimate rest period.
5. Discuss typical sources for collecting human factors-related data.
6. Discuss the following three types of occupational-related stressors:
   - Workload-related stressors.
   - Occupational frustration-related stressors.
   - Occupational change-related stressors.
7. Prove Eq. (3.10) using Eq. (3.5).
8. Assume that the error rate of a person performing a task in a power generation station is 0.005 errors per hour. Calculate his/her reliability during an 8-hour mission.
9. List at least thirteen reasons for the occurrence of human errors.
10. What are the main approaches for collecting human reliability and error data? Discuss each of these approaches in detail.

References

1. MIL-H-46855 (1972) Human engineering requirements for military systems, equipment, and facilities. Department of Defense, Washington, D.C., May 1972
2. Dhillon BS (2009) Human reliability, error, and human factors in engineering maintenance: with reference to aviation and power generation. CRC Press, Boca Raton
3. Woodson WE (1981) Human factors design handbook. McGraw-Hill Book Company, New York
4. Dhillon BS (1986) Human reliability: with human factors. Pergamon Press, New York
5. Chapanis A (1996) Human factors in systems engineering. Wiley, New York
6. Dhillon BS (1996) Engineering design: a modern approach. Richard D. Irwin Inc, Chicago
7. Dhillon BS (1998) Advanced design concepts for engineers. Technomic Publishing Company, Lancaster
8. McCormick EJ, Sanders MS (1982) Human factors in engineering and design. McGraw-Hill Book Company, New York
9. AMCP 706-134 (1972) Engineering design handbook: maintainability guide for design. Prepared by the United States Army Material Command, 5001 Eisenhower Avenue, Alexandria, Virginia
10. AMCP 706-133 (1976) Engineering design handbook: maintainability engineering theory and practice. Prepared by the United States Army Material Command, 5001 Eisenhower Avenue, Alexandria, Virginia

11. Lederman S (1978) Heightening tactile impression of surface texture. In: Gordon G (ed) Active touch. Pregamon Press, New York, pp 40–44
12. Altman JW et al (1961) Guide to design mechanical equipment for maintainability. Report no. ASD-TR-61-381, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio
13. Peters GA, Adams BB (1959) Three criteria for readable panel markings. Prod Eng 30(21):55–57
14. Oborne DJ (1982) Ergonomics at work. Wiley, New York
15. Murrell KFH (1965) Human performance in industry. Reinhold, New York
16. Meister D (1966) Human factors in reliability. In: Ireson WG (ed) Reliability handbook. McGraw-Hill Book Company, New York, pp 400–415
17. Beech HR, Burns LE, Sheffield BF (1982) A behavioural approach to the management of stress. Wiley, New York
18. Dhillon BS (1980) On human reliability: bibliography. Microelectron Reliab 20:371–373
19. Shooman ML (1968) Probabilistic reliability: an engineering approach. McGraw-Hill Book Company, New York
20. Meister D (1962) The problem of human-initiated failures. In: Proceedings of the 8th national symposium on reliability and quality control, pp 234–239
21. Hammer W (1980) Product safety management and engineering. Prentice Hall Inc., Englewood Cliffs
22. Meister D (1971) Human factors: theory and practice. Wiley, New York
23. McCormack RL (1961) Inspection accuracy: a study of the literature. Report no. SCTM 53-61 (14), Sandia Corporation, Albuquerque, New Mexico
24. Meister D (1984) Human reliability. In: Muckler FA (ed) Human factors review. Human Factors Society, Santa Monica, California, pp 13–53
25. Dhillon BS (1990) Human error data banks. Microelectron Reliab 30:963–971
26. Dhillon BS, Singh C (1981) Engineering reliability: new techniques and applications. Wiley, New York
27. Munger SJ, Smith RW, Payne D (1962) An index of electronic equipment operability: data store. Report no. AIR-C43-1/62 RP(1), American Institute for Research, Pittsburgh, Pennsylvania
28. Urmston R (1971) Operational performance recording and evaluation data system (OPREDS). Descriptive Brochures, Code 3400, Navy Electronics Laboratory Center, San Diego, California, Nov 1971
29. Reporting Procedures Manual for the Nuclear Plant Reliability Data System (NPRDS) (1980) South-West Research Institute, San Antonio, Texas, Dec 1980
30. Topmiller DA, Eckel JS, Kozinsky EJ (1982) Human reliability data bank for nuclear power plant operations: a review of existing human reliability data banks. Report no. NUREG/CR2744/1, U.S. Nuclear Regulatory Commission, Washington, D.C
31. Irwin IA, Levitz JJ, Freed AM (1964) Human reliability in the performance of maintenance. Report no. LRP 317/TDR-63-218, Aerojet-General Corporation, Sacramento, California
32. Aviation Safety Reporting Program (1979) FAA advisory circular no. 00-46B. Federal Aviation Administration (FAA), Washington, D.C., 15 Jun 1979

Chapter 4
General Methods for Performing Human Reliability and Error Analysis in Power Plants

4.1 Introduction

Over the years, a vast amount of the literature in the areas of reliability, human factors, and safety has appeared in the form of books, journal articles, technical reports, and conference proceedings articles [1–3]. Many new methods have been developed in these very three areas. Some of these methods are being used quite successfully across many diverse areas including engineering design, engineering maintenance, health care, and management. Some examples of these methods are fault tree analysis (FTA), failure modes and effect analysis (FMEA), and the Markov method.

The FTA method was developed in the early 1960s to analyse rocket launch control systems from the safety aspect [1]. Nowadays, it is being used in many diverse areas such as aerospace, management, nuclear power generation, and health care. FMEA was developed in the early 1950s to perform reliability analysis of engineering systems. Nowadays, it is also being used across many diverse areas such as aerospace, health care, and power generation. The Markov method was developed by Andrei Andreyevich Markov (1856–1922), a Russian mathematician, and is a highly mathematical approach frequently used to perform reliability and safety analyses of engineering systems. Nowadays, it is also being used in areas such as health care, maintenance, and power generation.

This chapter presents a number of methods and approaches, extracted from the published literature on reliability, human factors, and safety, considered useful to perform human reliability and error analysis in power plants.

4.2 Error-Cause Removal Programme (ECRP)

This method was developed to reduce human errors to some tolerable level in the area of production operations, and it may simply be described as the production worker-participation programme for reducing human errors [4]. The method

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_4,

emphasizes preventive measures rather than the remedial ones. Some examples of the production workers are inspection and maintenance personnel, assembly personnel, and machinists.

All involved production workers are divided into groups/teams, and in turn, each group/team has a coordinator with necessary technical and group skills. The maximum number of team members is restricted to twelve persons. Each team holds its meeting regularly, in which team members present error-likely and error reports. The reports are reviewed, and then, appropriate recommendations are made to take necessary remedial measures. The team coordinators present all the recommendations to appropriate management personnel for their actions.

It is to be noted with care that human factors and other specialists also assist both team and management personnel with respect to various factors including evaluation and implementation of the proposed design-related solutions. More specifically, the ECRP is composed of the following seven basic elements [2, 4, 5]:

- **Element I**: All personnel involved with ECRP are properly educated about the ECRP usefulness.
- **Element II**: Management clearly values the efforts of production personnel with respect to ECRP.
- **Element III**: Management ensures the implementation of the most promising proposed design-related solutions.
- **Element IV**: All involved coordinators and workers are trained properly in data collection and analysis techniques.
- **Element V**: The effects of changes in the production process by considering the ECRP inputs are determined by the human factors and other specialists.
- **Element VI**: Production personnel report and evaluate errors and error-likely situations and propose possible design solutions to eradicate causes of errors.
- **Element VII**: Human factors and other specialists review all the proposed design solutions in regard to cost.

Finally, three guidelines considered most useful concerning ECRP are as follows [4, 5]:

- Review with care each work redesign recommended by the team with respect to factors such as increment in job satisfaction, cost-effectiveness, and the degree of error reduction.
- Focus data collection to items such as errors, error-likely conditions, and accident-prone conditions.
- Restrict to highlighting those work conditions that need redesign for reducing the error occurrence potential.

4.3 Man–Machine Systems Analysis

This method was developed in the early 1950s and is concerned with reducing human error-caused unwanted effects to some acceptable level in a system. The method is composed of ten steps shown in Fig. 4.1 [5, 6].

4.4 Failure Modes and Effect Analysis

This is probably the most widely used method to perform reliability analysis of engineering systems in industry. FMEA may simply be described as an effective approach to perform analysis of each potential failure mode in a given system for determining the effects of such failure modes on the entire system [7]. When the effect of each failure mode is classified according to its severity, the method is known as failure mode effects and critical analysis (FMECA).

The history of FMEA goes back to the early 1950s, and it was developed by the United States Navy's Bureau of Aeronautics and was called "Failure Analysis" [8]. Subsequently, "Failure Analysis" was renamed to "Failure Effect Analysis" and the successor to the Bureau of Aeronautics (i.e. Bureau of Naval Weapons) introduced "Failure Effect Analysis" into its new specification on flight controls [9]. Needless to say, National Aeronautics and Astronautics Administration (NASA) extended the FMEA functions and then renamed FMEA to FMECA [10].

The following seven main steps are followed to perform FMEA [1, 5, 11]:

- **Step 1**: Define system boundaries and all its associated requirements in detail.
- **Step 2**: List system subsystems and parts.
- **Step 3**: Identify and describe each part and list its failure modes.
- **Step 4**: Assign probabilities or failure rates to each part's failure modes.
- **Step 5**: List effect or effects of each and every failure mode on subsystem, system, and plant.
- **Step 6**: Enter remarks for all failure modes.
- **Step 7**: Review critical failure modes and take appropriate actions.

There are many advantages of performing FMEA, including a systematic approach for classifying hardware failures, useful for identifying safety concerned to be focused on, useful to reduce engineering changes, useful to improve customer satisfaction, a visibility tool for management, useful to improve communication among design interface personnel, a useful approach that starts from the detailed level and works upward, useful for providing safeguard against repeating the same mistakes in the future, easy to understand, and useful for reducing development cost and time [5, 11, 12].

All in all, additional information on FMEA is available in Refs. [11–13].

Step 1:	Define system goals and functions
Step 2:	Define concerned situational characteristics (i.e., the performance shaping factors such as illumination and air quality under which tasks have to be performed)
Step 3:	Define characteristics (e.g., experience, skills, training, and motivation) of involved individuals
Step 4:	Define jobs performed by involved individuals
Step 5:	Analyze jobs with respect to identifying potential error-likely situations and other associated difficulties
Step 6:	Estimate chances or other information with respect to potential human error occurrence
Step 7:	Determine the likelihood of failure to detect and rectify a potential human error
Step 8:	Determine the possible consequences of failure to detect potential human errors
Step9:	Recommend appropriate changes
Step 10:	Re evaluate each and every change by repeating most of the above steps

Fig. 4.1 Man–machine systems analysis steps

4.5 Probability Tree Method

This method is often used for performing task analysis in the technique for the human error rate prediction (THERP) [14]. In performing task analysis, the method diagrammatically represents critical human actions and other associated events. More specifically, diagrammatic task analysis is denoted by the probability tree branches. The branching limbs denote outcomes (i.e. success or failure) of each and every event related to a problem under consideration, and each branch is assigned probability of occurrence.

There are many advantages of the probability tree method. The three important ones are as follows [11, 14]:

- Simplified mathematical computations.
- An effective visibility tool.
- An effective tool for predicting the quantitative effects of errors.

Also, it is to be noted that this method can incorporate, with some modifications, factors such as interaction effects, emotional stress, and interaction stress [2]. More detailed information on the method is available in Refs. [2, 14].

The application of this method to a human reliability-related power generation system problem is demonstrated through the following example:

Example 4.1 A power generation system operator performs two independent tasks: a and b. Task a is performed before task b, and each of these tasks can be performed either correctly or incorrectly. In other words, the incorrectly performed tasks are the only errors that can occur in this situation.

Develop a probability tree for this example and obtain an expression for the probability of failure to accomplish the overall mission by the power generation system operator.

This example states that the power generation system operator first performs task a correctly or incorrectly and then proceeds to perform task b. Task b can also be performed correctly or incorrectly by the operator. This complete scenario is depicted by the probability tree shown in Fig. 4.2.
The four symbols used in Fig. 4.2 are defined below.

a denotes the event that task a is performed correctly.
$\bar{a}$ denotes the event that task a is performed incorrectly.
b denotes the event that task b is performed correctly.
$\bar{b}$ denotes the event that task b is performed incorrectly.

By examining Fig. 4.2, it can be concluded that there are three distinct possibilities (i.e. $\mathrm{a}\overline{\mathrm{b}}, \overline{\mathrm{ab}}$, and $\overline{\mathrm{a}}\overline{\mathrm{b}}$) for having an overall mission failure. Thus, the probability of failure to accomplish the overall mission by the power generation system operator is given by

$$P_{\mathrm{pgso}} = P\left(\mathrm{a}\overline{\mathrm{b}} + \overline{\mathrm{ab}} + \overline{\mathrm{a}}\overline{\mathrm{b}}\right) \tag{4.1}$$

where

P_{pgso} is the probability of failure to accomplish the overall mission by the power generation system operator.

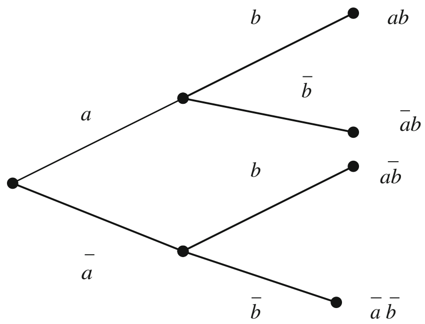

Fig. 4.2 Probability tree for the power generation system operator performing tasks a and b

For mutually exclusive and independent events using Eq. (4.1), we get

$$P_{\text{pgso}} = P_{\text{a}}P_{\bar{\text{b}}} + P_{\bar{\text{a}}}P_{\text{b}} + P_{\bar{\text{a}}}P_{\bar{\text{b}}} \tag{4.2}$$

where

P_{a} is the probability of performing task a correctly.
$P_{\bar{\text{a}}}$ is the probability of performing task a incorrectly.
P_{b} is the probability of performing task b correctly.
$P_{\bar{\text{b}}}$ is the probability of performing task b incorrectly.

Since $P_{\bar{\text{a}}} = 1 - P_{\text{a}}$ and $P_{\bar{\text{b}}} = 1 - P_{\text{b}}$, Eq. (4.2) reduces to

$$\begin{aligned} P_{\text{pgso}} &= P_{\text{a}}(1 - P_{\text{b}}) + (1 - P_{\text{a}})P_{\text{b}} + (1 - P_{\text{a}})(1 - P_{\text{b}}) \\ &= 1 - P_{\text{a}}P_{\text{b}} \end{aligned} \tag{4.3}$$

Example 4.2 Assume that in Example 4.1, the probabilities of failure to accomplish tasks a and b by the power generation system operator are 0.15 and 0.05, respectively. Calculate the probability of failure to accomplish the overall mission by the operator.

Thus, we have

$$P_{\text{a}} = 1 - P_{\bar{\text{a}}} = 1 - 0.15 = 0.85$$
$$P_{\text{b}} = 1 - P_{\bar{\text{b}}} = 1 - 0.05 = 0.95$$

By inserting the above-calculated values into Eq. (4.3), we obtain

$$\begin{aligned} P_{\text{pgso}} &= 1 - (0.85)(0.95) \\ &= 0.1925 \end{aligned}$$

Thus, the probability of failure to accomplish the overall mission by the power generation system operator is 0.1925.

4.6 Markov Method

This method was developed by Andrei Andreyevich Markov (1856–1922), a Russian mathematician, and is frequently used to perform various types of reliability-related studies in industry. The method has also been used to perform human reliability analysis [2]. Thus, it could be a very useful tool to perform various types of human reliability analysis in the area of power generation.

The Markov method is based on the following three assumptions [11, 15]:

- The probability of the occurrence of a transition from one system state to another in the finite time interval Δt is given by $\theta\Delta t$, where θ is the constant transition rate from one system state to another.
- The probability of more than one occurrences in the finite time interval Δt from one system state to another is negligible (e.g. $(\theta\Delta t)(\theta\Delta t) \rightarrow 0$).
- All occurrences are independent.

The application of the Markov method to perform human reliability analysis in the area of power generation is demonstrated through the following example:

Example 4.3 Assume that a power generation system operator makes errors at a constant rate, θ. The state space diagram shown in Fig. 4.3 describes this scenario in more detail. The numerals shown in the state space diagram denote system states. By using the Markov method develop expressions for the operator's reliability at time t and mean time to human error.

With the aid of the Markov method, we write down the following equations for the state space diagram shown in Fig. 4.3 [11, 15]:

$$P_0(t + \Delta t) = P_0(t)(1 - \theta\Delta t) \tag{4.4}$$

$$P_1(t + \Delta t) = P_0(t)(\theta\Delta t) + P_1(t) \tag{4.5}$$

where

θ is the constant error rate of the power generation system operator.

$P_0(t + \Delta t)$ is the probability that the operator is performing his/her task normally or correctly at time $(t + \Delta t)$.

$P_1(t + \Delta t)$ is the probability that the operator has committed an error at time $(t + \Delta t)$.

$\theta\Delta t$ is the probability of human error by the power generation system operator in finite time interval Δt.

$(1 - \theta\Delta t)$ is the probability of no human error by the power generation system operator in finite time interval Δt.

$P_0(t)$ is the probability that the operator is performing his/her task normally at time t.

$P_1(t)$ is the probability that the operator has committed an error at time t.

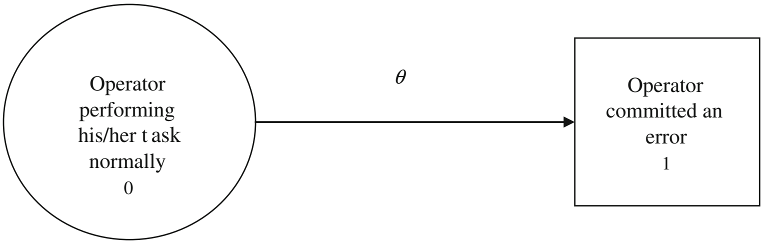

Fig. 4.3 State space diagram representing the power generation system operator

By rearranging Eqs. (4.4)–(4.5) and taking the limit as $\Delta t \to 0$, we obtain

$$\lim_{\Delta t \to 0} \frac{P_0(t+\Delta t) - P_0(t)}{\Delta t} = \frac{dP_0(t)}{dt} = -\theta P_0(t) \tag{4.6}$$

$$\lim_{\Delta t \to 0} \frac{P_1(t+\Delta t) - P_1(t)}{\Delta t} = \frac{dP_1(t)}{dt} = \theta P_0(t) \tag{4.7}$$

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

By solving Eqs. (4.6)–(4.7) with the aid of Laplace transforms, we obtain

$$P_0(s) = \frac{1}{s+\theta} \tag{4.8}$$

$$P_1(s) = \frac{\theta}{s(s+\theta)} \tag{4.9}$$

where

s is the Laplace transform variable.

Taking the inverse Laplace transforms of Eqs. (4.8)–(4.9), we get

$$P_0(t) = e^{-\theta t} \tag{4.10}$$

$$P_1(t) = 1 - e^{-\theta t} \tag{4.11}$$

Thus, reliability of the power generation system operator is given by

$$R_{pgso}(t) = P_0(t) = e^{-\theta t} \tag{4.12}$$

where

$R_{pgso}(t)$ is the reliability of the power generation system operator at time t.

The power generation system operator's mean time to human error is given by [11]

$$
\begin{aligned}
\mathrm{MTTHE}_{\mathrm{pgso}} &= \int_0^{\infty} R_{\mathrm{pgso}}(t)\mathrm{d}t \\
&= \int_0^{\infty} e^{-\theta t}\mathrm{d}t \\
&= \frac{1}{\theta}
\end{aligned}
\tag{4.13}
$$

where

$\mathrm{MTTHE}_{\mathrm{pgso}}$ is the mean time to human error of the power generation system operator.

Example 4.4 A power generation system operator's constant error rate is 0.0008 errors/h. Calculate the operator's mean time to human error and reliability for a 8-h mission.

By inserting the given data values into Eqs. (4.13) and (4.12), we obtain

$$
\begin{aligned}
\mathrm{MTTHE}_{\mathrm{pgso}} &= \frac{1}{0.0008} \\
&= 1{,}250\,\mathrm{h}
\end{aligned}
$$

and

$$
\begin{aligned}
R_{\mathrm{pgso}}(8) &= e^{-(0.0008)(8)} \\
&= 0.9936
\end{aligned}
$$

Thus, the power generation system operator's mean time to human error and reliability are 1,250 h and 0.9936, respectively.

4.7 Fault Tree Analysis

This is a widely used method to perform reliability analysis of engineering systems in industry, particularly in the area of nuclear power generation. The method was developed in the early 1960s to perform safety analysis of the Minuteman Launch Control System at the Bell Telephone Laboratories [1].

A fault tree may simply be described as a logical representation of the relationship of primary fault events that may cause the occurrence of a specified undesirable event, called the "top event". It is depicted using a tree structure with logic gates such as AND and OR.

It is to be noted that there is probably nothing basically new regarding the principle used for the generation of fault trees. It consists of successively asking the following question:

"What are the possible ways for this fault event to occur?"

Nonetheless, the newness lies in the utilization of logic operators (i.e. gates) in the organization and graphical representation of the logic structure relating the primary or basic fault events to the top event.

In the construction of fault trees, there are many symbols used. The four basic ones are shown in Fig. 4.4 [1, 16]. Information on other symbols is available in Refs. [1, 11, 16, 17].

All the four symbols in Fig. 4.4 are described below.

- **Circle**. It denotes a primary or basic fault event or the failure of an elementary component or part.
- **Rectangle**. It represents a fault event which results from the logical combination of fault events through the input of a logic gate.
- **AND gate**. It denotes that an output fault event will occur only if all of the fault events occur.
- **OR gate**. It denotes that an output event will occur if one or more of the input fault events occur.

Usually, the following steps are followed in performing FTA [11, 18]:

- **Step 1**: Define the system and analysis associated assumptions.
- **Step 2**: Identify the system undesirable or top fault event (i.e. the system undesirable or top fault event to be investigated).
- **Step 3**: Identify all the causes that can make the top fault event to occur, by using fault tree symbols and the logic tree format.
- **Step 4**: Develop the fault tree to the lowest level of detail as per the requirements.
- **Step 5**: Perform analysis of the completed fault tree with respect to factors such as gaining proper insight into the unique modes of product faults and understanding the proper logic and the interrelationships among various fault paths.
- **Step 6**: Determine most appropriate corrective actions.
- **Step 7**: Document the analysis and follow up on the identified corrective actions.

Example 4.5 Assume that a power generation system operator is required to perform task Z. The task is composed of three subtasks: i, j, and k. If one or more of these subtasks is/are performed incorrectly, the task Z will be performed incorrectly. Subtask i composed of two steps: m and n. Both these steps must be performed incorrectly for subtask i to be performed incorrectly. Subtask j is also composed of two steps: a and b. If one or both of these two steps is/are performed incorrectly, the subtask j will be performed incorrectly.

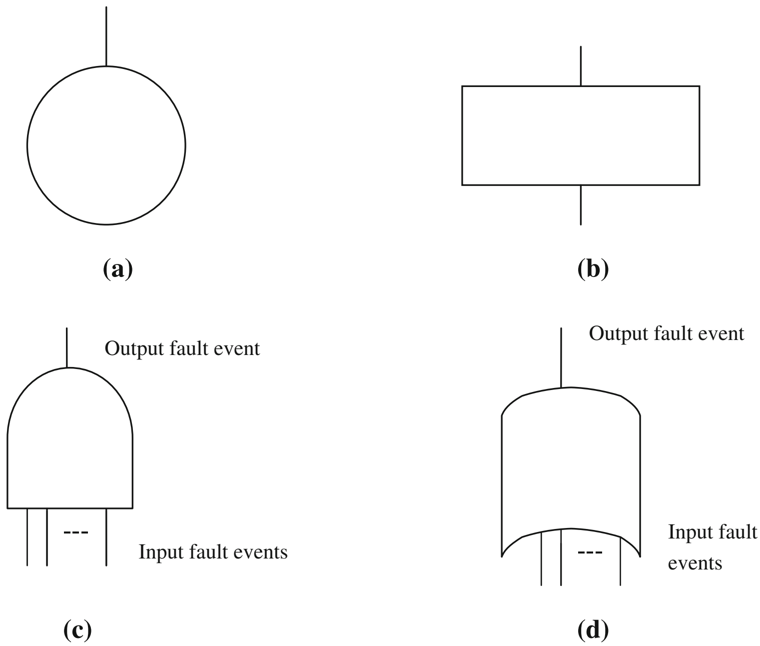

Fig. 4.4 Basic fault tree symbols: **a** Circle, **b** Rectangle, **c** AND gate, **d** OR gate

If subtasks and steps are independent, develop a fault tree for the undesired event (i.e. top event): power generation system operator will not perform the task, Z, correctly.

By using the symbols in Fig. 4.4, the fault tree shown in Fig. 4.5 for this example is developed. Each fault event in Fig. 4.5 is labelled as $E_1, E_2, E_3, E_4, E_5, E_6, E_7,$ and E_8.

4.7.1 Fault Tree Probability Evaluation

The probability of occurrence of the top fault event of a fault tree can be calculated when the occurrence probabilities of primary or basic fault events are know. This can only be calculated by first calculating the probability of occurrence of the output (i.e. resultant) fault events of lower and intermediate logic gates such as OR and AND. Thus, the occurrence probability of the OR gate output fault event is expressed by [11].

$$P(x_0) = 1 - \prod_{j-1}^{m} \left\{1 - P\left(x_j\right)\right\} \tag{4.14}$$

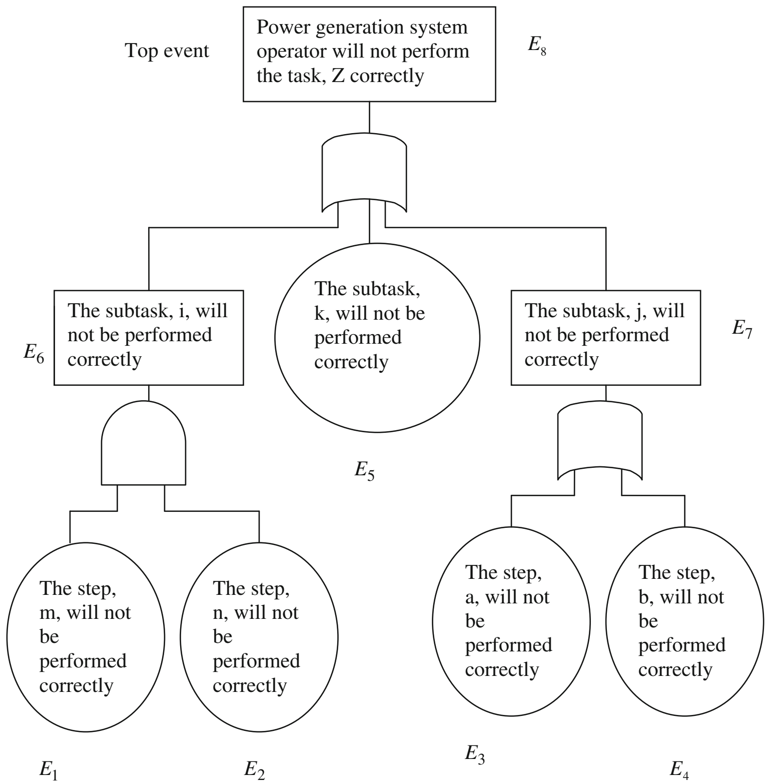

Fig. 4.5 A fault tree for the unsuccessful performance of task, Z, by the power generation system operator

where

$P(x_0)$ is the occurrence probability of the output fault event, x_0, of the OR gate.

m is the total number of input fault events of the OR gate.

$P(x_j)$ is the probability of occurrence of the OR gate input fault event, x_j; for $j = 1, 2, 3, \ldots, m$.

Similarly, the occurrence probability of the AND gate output fault event is given by [11]

$$P(y_0) = \prod_{j=1}^{k} P(y_j) \tag{4.15}$$

where

$P(y_0)$ is the occurrence probability of the output fault event, y_0, of the AND gate.

k is the total number of input fault events of the AND gate.

$P(y_j)$ is the probability of occurrence of the AND gate input fault event y_j; for $j = 1, 2, 3, \ldots, k$.

Example 4.6 Assume that the occurrence probabilities of fault events E_1, E_2, E_3, E_4, and E_5 in Fig. 4.5 fault tree are 0.01, 0.03, 0.04, 0.05, and 0.02, respectively.

Calculate the occurrence probability of the top fault event (i.e. power generation system operator will not perform the task, Z, correctly) and then redraw the fault tree in Fig. 4.5 with the given and calculated fault event occurrence probability values.

By substituting the given data values into Eq. (4.15), we obtain the following probability value, for the occurrence of event E_6: the subtask, i, will not be performed correctly:

$$\begin{aligned} P(E_6) &= P(E_1)P(E_2) \\ &= (0.01)(0.03) \\ &= 0.0003 \end{aligned}$$

Similarly, by inserting the specified data values into Eq. (4.14), we obtain the following probability value, for the occurrence of event E_7: the subtask, j, will not be performed correctly:

$$\begin{aligned} P(E_7) &= 1 - \{1 - P(E_3)\}\{1 - P(E_4)\} \\ &= 1 - \{1 - 0.04\}\{1 - 0.05\} \\ &= 1 - (0.96)(0.95) \\ &= 0.088 \end{aligned}$$

By inserting the above two calculated values and the specified data value for fault event E_5 into Eq. (4.14), we obtain the following probability value for the occurrence of the top event, E_8: power generation system operator will not perform the task, Z, correctly:

$$\begin{aligned} P(E_8) &= 1 - \{1 - P(E_6)\}\{1 - P(E_5)\}\{1 - P(E_7)\} \\ &= 1 - \{1 - 0.0003\}\{1 - 0.02\}\{1 - 0.088\} \\ &= 0.1065 \end{aligned}$$

Thus, the occurrence probability of the top fault event (i.e. power generation system operator will not perform the task, Z, correctly) is 0.1065. The fault tree with the calculated and given fault event occurrence probability values is shown in Fig. 4.6.

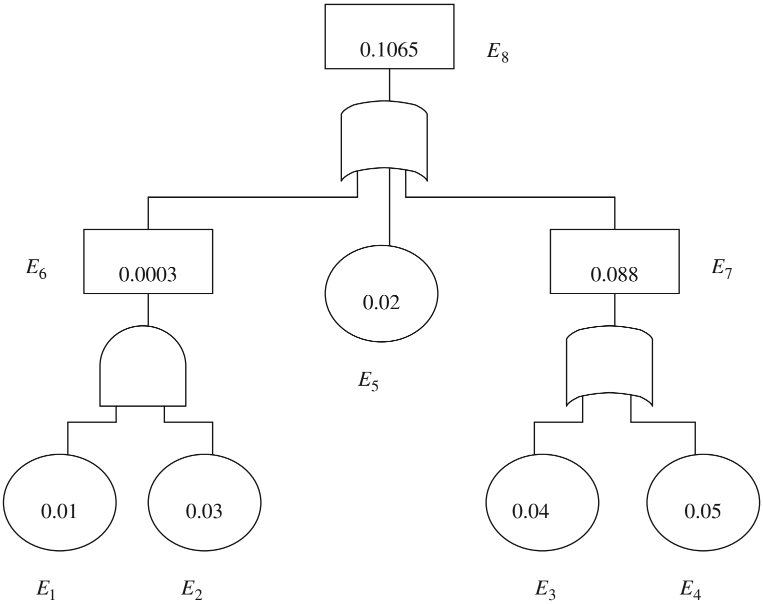

Fig. 4.6 Redrawn Fig. 4.5 fault tree with the calculated and given fault occurrence probability values

4.7.2 Fault Tree Analysis Advantages and Disadvantages

Just like any other reliability analysis approach, the FTA method too has its advantages and disadvantages. Thus, some of the advantages of the FTA method are as follows [11]:

- It provides insight into the system behaviour and can handle complex systems more easily than any other method.
- It serves as a graphic aid for system management and provides options for management and others to perform either quantitative or qualitative reliability analysis.
- It highlights failures deductively.
- It allows concentration on one specific failure at a time and requires the involved analyst to comprehend thoroughly the system under consideration before starting the FTA process.

In contrast, some of the disadvantages of the FTA method are as follows [11]:

- It is a time consuming and a costly method.
- Its end results are difficult to check.
- It considers parts/components in either working or failed state. More clearly, the partial failure states of parts/components are quite difficult to handle.

4.8 Problems

1. Describe error-cause removal programme.
2. What are the guidelines considered most useful concerning ECRP?
3. Describe man–machine systems analysis.
4. Describe failure modes and effect analysis.
5. List at least six advantages of failure modes and effect analysis.
6. Assume that a power generation system operator performs three independent tasks: x, y, and z. Task x is performed before task y, and task y before task z. Each of these three tasks can be performed either correctly or incorrectly. In other words, the incorrectly performed tasks are the only errors that can occur in this situation.
   Develop a probability tree for this example and obtain an expression for the probability of failure to accomplish the overall mission by the power generation system operator.
7. Assume that in the proceeding question (i.e. question no. 6), the probabilities of failure to accomplish tasks x, y, and z by the power generation system operator are 0.2, 0.1, and 0.05, respectively. Calculate the probability of failure to accomplish the overall mission by the operator.
8. Prove Eqs. (4.10) and (4.11) by using Eqs. (4.6) and (4.7).
9. Describe the following terms used in the fault tree construction with the aid of diagrams:
   - OR gate
   - Resultant event
   - Basic event
   - AND gate.
10. What are the advantages and disadvantages of the FTA method?

References

1. Dhillon BS, Singh C (1981) Engineering reliability: new techniques and applications. Wiley, New York
2. Dhillon BS (1986) Human reliability with human factors. Pergamon Press, New York
3. Dhillon BS (2003) Engineering safety: fundamentals, techniques, and applications. World Scientific Publishing, New Jersey
4. Swain AD (1973) An error-cause removal program for industry. Hum Factors 12:207–221
5. Dhillon BS (2007) Human reliability and error in transportation systems. Springer Inc, London
6. Miller RB (1953) A method for man-machine task analysis, Report No. 53-137, Wright Air Development Center, Wright-Patterson Air Force Base, U.S. Air Force (USAF), Ohio
7. Omdahl TP (ed) (1988) Reliability, availability, and maintainability (RAM) dictionary. American Society of Quality Control (ASQC) Press, Milwaukee

8. MIL-F-18372 (Aer.) General specification for design, installation, and test of aircraft flight control systems. Bureau of Naval Weapons, Department of the Navy, Washington, D.C., Paragraph 3.5.2.3
9. Continho JS (1963–1964) Failure effect analysis, Transactions of the New York Academy of Sciences, vol 26, Series II, pp 564–584
10. Jordan WE (1972) Failure modes, effects and criticality analyses. In: Proceedings of the annual reliability and maintainability symposium, pp 30–37
11. Dhillon BS (1999) Design reliability: fundamentals and applications. CRC Press, Boca Raton
12. Palady P (1995) Failure modes and effects analysis. PT Publications, West Palm Beach
13. Dhillon BS (1992) Failure modes and effect analysis. Microelectron Reliab 32:719–731
14. Swain AD (1963) A method for performing a human-factors reliability analysis. Report No. SCR-685, Sandia Corporation, Albuquerque, New Mexico, August 1963
15. Shooman ML (1968) Probabilistic reliability: an engineering approach. McGraw Hill Book Company, New York
16. Schroder RJ (1970) Fault tree for reliability analysis. In: Proceedings of the annual symposium on reliability, pp 170–174
17. Risk analysis using the fault tree technique. Flow research report, Flow Research, Inc., Washington, D.C., 1973
18. Grant Ireson W, Coombs CF, Moss RY (ed) (1996) Handbook of reliability engineering and management, McGraw-Hill Book Company, New York

Chapter 5
Specific Human Reliability Analysis Methods for Nuclear Power Plants

5.1 Introduction

Nuclear power plants generate about 16 % of the world's electricity, and there are over 440 commercial nuclear reactors operating in 30 countries, with another 65 reactors under construction [1]. Furthermore, in 2007, 104 nuclear power plants generated around 19 % of the electricity consumed in the United States [2]. Needless to say, nuclear power plants have become an important element in power generation throughout the world.

Humans play an important role in nuclear power generation and their reliability has become an important issue as human error can result in nuclear power plant accidents such as Chernobyl and Three Mile Island. Furthermore, as per Refs. [3, 4], a study of Licensee Event Reports (LERs) conducted by the United States Nuclear Regulatory Commission (USNRC) indicates that upward of 65 % of nuclear system failures involve human error to a certain degree.

Over the years to perform human reliability analysis (HRA) is nuclear power plants, a number of methods have been developed. These methods include technique for human error rate prediction (THERP), task analysis-linked evaluation technique (TALENT), cognitive reliability and error analysis method (CREAM), and a technique for human event analysis (ATHEANA). This chapter presents important aspects of HRA methods and a number of methods used in nuclear power plants.

5.2 Incorporation of the Human Reliability Analysis Integrally into a Probabilistic Risk Assessment and Requirements for Human Reliability Analysis Method

As the risk associated with a nuclear power plant is very much dependent on the reliability of all involved humans and their interactions with the equipment and controls in the plant, an HRA is an integral part of probabilistic risk assessment (PRA).

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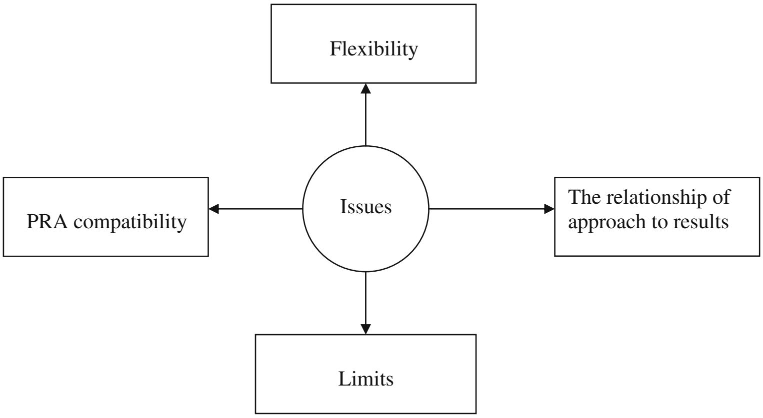


Fig. 5.1 Issues concerning the incorporation of the HRA integrally into a PSA

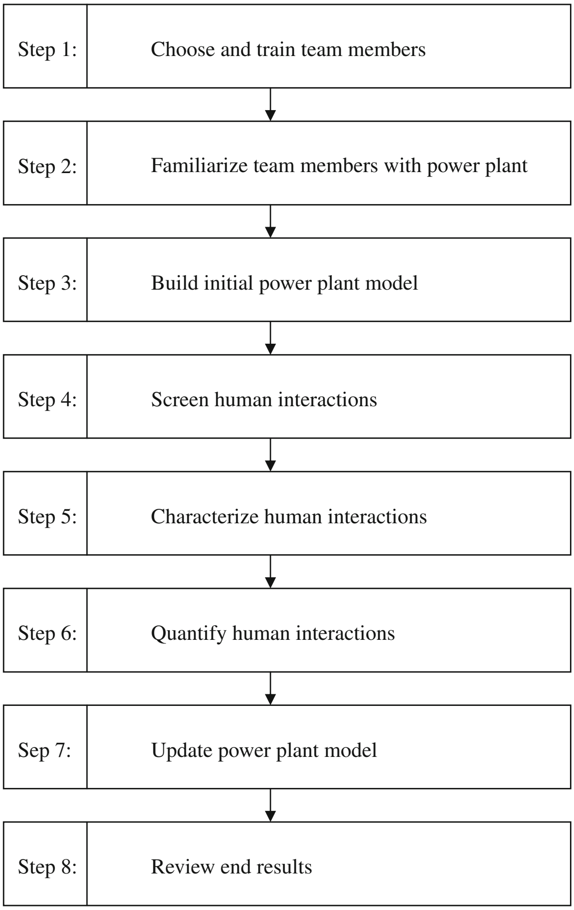
Thus, the incorporation of the HRA integrally into a PRA includes the four issued shown in Fig. 5.1 [5].

The issue "The relationship of approach to results" is basically concerned with the relationship between the way in which an HRA is carried out, its philosophy, and the end results or the insights that may be obtained. The issue "PRA compatibility" is concerned with the compatibility of an HRA with the PRA of which it is an element/part. It is to be noted that the risk applications of PRA require the HRA process to specify clearly human interaction-related events in qualitative detail, adequate for guiding the risk management efforts from the perspective of human factors.

The issue "Limits" is concerned with the HRA limits or the limits of HRA results. Thus, HRA results should be documented in such a way that is clearly understandable to general PRA users. Furthermore, the results should be easily traceable to their data sources, basic assumptions, and models. Finally, the issue "Flexibility" is concerned with the flexibility needed in using behavioural science technologies associated with HRA. It is to be noted that HRA is a relatively immature method; however, the method is based on the scientific disciplines developed in the area of behavioural sciences with their inherent uncertainties to a certain degree. All in all, HRA should be flexible enough for accommodating new findings and model developments effectively while structured enough to be tractable and repeatable properly.

As HRA forms an important element of nuclear power plants' probabilistic safety assessment (PSA) studies, the objective of the PSA ought to be reflected in the choice of the HRA method [6]. This way, if the PSA were to be used by a regulatory body personnel for assessing the general risk of the industry, one would make use of generic technique/method representative of a nominal nuclear power plant. Needless to say, HRA quality is one of the requirements to setting PSA usage. Quality is reflected in both what technique/method is selected and how it is used.

Fig. 5.2 Human reliability analysis (*HRA*) process steps



In order to achieve a "good" quality rating, one has to tie the technique/method to the use of a non-generic technique/method supported by the use of power plant personnel (i.e. experts in their specializations) as well as feedback received from plant experience and the application of the simulator. Additional information on requirements for an HRA method is available in Ref. [6].

5.3 Human Reliability Analysis Process Steps and Their End Products

HRA process for use in nuclear power plants is made up of eight steps as shown in Fig. 5.2 [5]. These steps result in various types of end results or products. The corresponding result or product of each of these steps is presented below in parentheses [5].

- Step 1: (Set of various types of skills embodied in an integrated team.)
- Step 2: (Initial identification of human functions and activities. Furthermore, problems can be spotted although without much risk context yet.)
- Step 3: (Most important human interactions identified, system interactions identified, all major systems modelled, and a measure of the defence barriers against major classes of off-normal events.)
- Step 4: (Important human interactions highlighted, initial quantification performed, and screening values chosen.)
- Step 5: (Failure modes, causes, effects, mechanisms, and influences of the important human interactions are determined.)
- Step 6: (Importance ranking, likelihood and uncertainties of important human interactions.)
- Step 7: (Interactions and recovery models added to model.)
- Step 8: (Confidence that end results make sense and can be utilized by plant personnel in risk applications.)

Additional information on HRA process steps and their end products/results is available in Ref. [5].

5.4 Human Reliability Analysis Methods

Over the years, many methods have been developed, directly or indirectly, for generating human error probabilities for application in the nuclear power industrial sector. Some of these methods are as follows [7–12]:

- Technique for human error rate prediction (THERP).
- Accident sequence evaluation program (ASEP).
- Success likelihood index method–multi-attribute utility decomposition (SLIM-MAUD).
- Human cognitive reliability model (HCR).
- A technique for human event analysis (ATHEANA).
- Standardized plant analysis risk–human reliability analysis (SPAR-H).
- Human error assessment and reduction technique (HEART).
- Cognitive reliability and error analysis method (CREAM).
- Justified human error data information (JHEDI).

The information requirements of THERP, SLIM, HCR, and ASEP are as follows [7, 13]:

- Appropriate description of the task and the action.
- The available procedures.
- The teams or individuals that have to carry out the task.
- The time required to carry out the task properly.
- The dependence of these different times.
- The technical systems and their associated dynamics.

- The dependence of the different tasks.
- Influence factors (e.g. skill, stress, and fatigue).
- Recovery factors for all the different tasks.
- The error type.
- The available total time for diagnosis and execution of a task correctly (i.e. total time window for action).
- The working media or the man–machine interface.
- Demands of cognition and action, the level of experience, and perception.

Additional information on the above information requirements is available in Ref. [13].

Eight of the above nine HRA methods are described below, separately, and the information on the remaining method (i.e. JHEDI) is available in Ref. [14].

5.4.1 A Technique for Human Event Analysis

This is a post-incident HRA method, and it was developed by the USNRC [15, 16]. Following were the main reasons to develop ATHEANA [14]:

- In understanding human error, the accident record and advances in behavioural sciences both clearly supported a stronger focus on the contextual factors, particularly plant conditions.
- Advances made in the area of psychology were integrated with the disciplines of human factors, engineering, and PRA when modelling human failure-related events.
- Human events modelled in earlier human reliability assessment/PRA models were considered to be inconsistent with the degree of roles that human operators have played in operational events.

Seven basic steps to the ATHEANA methodology are as follows [16, 17]:

- Step 1: Define and interpret with care the issue under consideration.
- Step 2: Define and detail the required scope of the analysis.
- Step 3: Describe with care the base-case scenario including the norm of operations within the environments, considering procedures and actions.
- Step 4: Define human failure events and/or unsafe actions which may effect the task under consideration.
- Step 5: Categorize the identified human failure events under two basic groups: safe and unsafe actions. An unsafe action may simply be described as an action in which the human operator in question may fail to perform a specified task or performs it incorrectly that in turn results in the unsafe operation of the system.
- Step 6: Search with care for any deviations from the base-case scenario with respect to any divergence in the general environmental operating behaviour in the context of the situational scenario.
- Step 7: Preparation for applying ATHEANA.

In ATHEANA, the probability of human failure event occurring is expressed by the following equation [9]:

$$P_{\text{hfe}} = P_{\text{efe}} P_{\text{usa}} P_{\text{np}} \tag{5.1}$$

where

P_{hfe} is the probability of human failure event occurrence

P_{efe} is the probability of error-forcing context

P_{usa} is the probability of unsafe action in the error-forcing context

P_{np} is the probability of non-recovery in the error-forcing context and given the occurrence of the unsafe action as well as the existence of additional evidence following the unsafe action.

There are many benefits and drawbacks of ATHEANA. Some of these are presented below, separately.

Benefits

- It increases the chances that the key risks concerning the human failure events in question have been identified.
- In comparison with many other HRA methods, it provides a much better and more holistic understanding of the context concerning the human factors known to be the cause of the incident.
- In comparison with many other HRA quantification methods, it allows for the consideration of a much wider range of performance shaping factors, as well as it does not require that these factors to be treated as independent.
- The methodology of this method makes it possible to estimate human error probabilities considering a variety of differing factors and combinations.

Drawbacks

- It fails to prioritize or establish details of the causal relationships between the types of human factors contributing to an incident.
- Another drawback of this method is that, from a probability risk assessment stance, there is no human error probability generated.

5.4.2 Cognitive Reliability and Error Analysis Method

This is a bidirectional analysis method that can be used for both accident analysis and performance prediction. It puts emphasis on the analysis of human actions' causes, i.e. human cognitive activities [9]. The basis for the method is the classification schemes of error modes and of various components of the organization, technology, and human triad, which incorporates organization-associated factors, technology-associated factors, and human-associated factors.

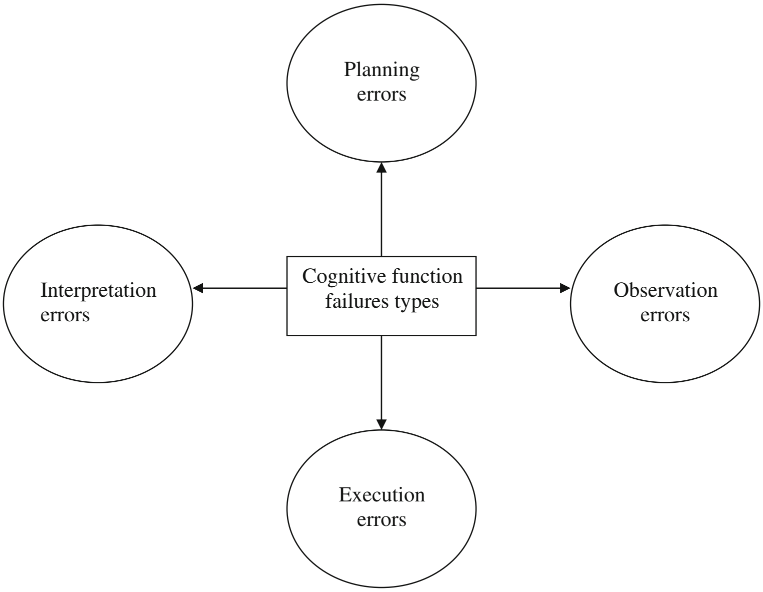


Fig. 5.3 Generic cognitive function failure types used in CREAM

The main objective of using this methodology is to assist analysts in the following four areas [18]:

- Area I: Highlight tasks, work, or actions within the system boundaries which necessitate or essentially depend on a range of human thinking and which are therefore quite vulnerable to variations in their reliability level.
- Area II: Highlight the surrounding environments in which the cognition of these conditions may be lowered and therefore determine what type of actions may lead to a probable risk.
- Area III: Compile an evaluation from the assessment of the various types of human performance-related outcomes as well as their effect on system safety. In turn, this can be used as part of the probability risk assessment.
- Area IV: Make appropriate suggestions/recommendations as to how highlighted error generating conditions may be improved to a certain degree and how the reliability of system can be improved while also lowering risk.

The generic cognitive function failure types used in CREAM are shown in Fig. 5.3 [9].

"Interpretation errors" include items such as faulty diagnosis (i.e. either an incorrect diagnosis or an incomplete diagnosis), delayed interpretation (i.e. not made in time), and decision error (i.e. either not making a decision or making an incorrect or incomplete decision). "Observation errors" include items such as observation of incorrect object (i.e. a response is given to the incorrect event or stimulus) and observation not made (i.e. overlooking a signal or a measurement).

"Execution errors" include items such as action performed at wrong time (i.e. either too late or too early), action of wrong type performed with respect to distance, speed, force, or direction; action performed out of sequence, and action missed. Finally, "Planning errors" include items such as priority error (i.e. selecting the wrong goal) and inadequate plan formulated (i.e. plan is either incomplete or directly wrong).

Some of the main benefits and drawbacks of CREAM are as follows [19]:

Benefits

- It is well structured, concise, and follows a well laid out system of procedure.
- It permits for the direct quantification of human error probability.
- It uses the same principles for predictive and retrospective analyses.

Drawbacks

- It needs a quite high level of resource use, including fairly lengthy time periods for completion.
- It fails to put forth potential means by which the highlighted errors can be cut down.

5.4.3 Technique for Human Error Rate Prediction

This method is used in the area of human reliability assessment/analysis to evaluate the probability of a human error occurring throughout the completion of a certain task. The method was developed at the Sandia Laboratories for the US Nuclear Regulatory Commission [20] and was the first method in human reliability assessment to come into broad use. It is based upon both plant data and expert judgements; thus, it relies on a large human reliability database that contains human error probabilities.

THERP is a total methodology to assess human reliability that clearly deals with task analyses (e.g. walk/talk through and documentation reviews), error representation and identification, and quantification of human error probabilities [21]. The key elements for completing the quantification process are decomposition of tasks into elements, assignment of nominal human error probabilities to each element, determination of effects of performance shaping factor on each element, calculation of effects of dependence between tasks, modelling an human reliability assessment event tree, and quantification of total task human error probability [14, 22].

In order to obtain the overall failure probability, the exact equation involves summing probabilities of all failure paths in the event tree under consideration.

Some of the benefits and drawbacks of THERP are as follows [7, 21]:

Benefits

- It can be used at all stages of design.
- It has a quite powerful methodology that can easily be audited.
- It is fairly well used in practice.

Drawbacks

- It can be quite time consuming and resource intensive.
- For many assessments, the level of detail included in this method may be quite excessive.
- It fails to offer proper guidance on modelling scenarios and the performance shaping factors' impact on performance.

5.4.4 Success Likelihood Index Method–Multi-Attribute Utility Decomposition

This method was developed by British researchers as a means of automating some of the mechanics of the existing success likelihood index method, for the US Nuclear Regulatory Commission [12, 23]. The method uses paired-comparison methods under the assumptions that similar tasks are grouped for analysis and lower and upper bound anchor point human error probabilities are determined for that group of tasks. Performance shaping factors are rated with respect to their quality and importance, and analysts' expert opinions are utilized to choose the bounding human error probabilities to determine the tasks to be similar enough to be compared as well as to assess the performance shaping factors.

Nonetheless, the SLIM-MAUD methodology breaks down into the following seven steps [24]:

- Step 1: Definition of situations and subsets.
- Step 2: Elicitation of performance shaping factors.
- Step 3: Rating all the tasks on the performance shaping factors.
- Step 4: Ideal point elicitation and scaling calculations.
- Step 5: Independent investigations/checks.
- Step 6: Weighting approach/procedure.
- Step 7: Success likelihood index (SLI) calculation.

It is to be noted that the strength of SLIM-MAUD lies in the paired-comparison approach that increases the analysis reliability. Furthermore, this method comes with a set of suggested performance shaping factors, although involved analysts are quite free to produce their own. Nonetheless, the method is considered atomistic because of its reliance on performance shaping factors [12].

5.4.5 Accident Sequence Evaluation Program

This method was designed as a simplified version to the THERP and its unique features include the following items [12, 25]:

- A detailed screening procedure for pre- and post-accident tasks.
- Inclusion of recovery factors.
- A simplified three-level account of dependency.
- Separate human error probabilities for pre- and post-accident tasks.
- Use of tables and software to provide uncertainty bounds.
- Tables to account for the influence of available time on the error probability.
- Consideration of the role of diagnosis in error and recovery.

The handling of the human error probability characterizes the distinction between this method (i.e. ASEP) and THERP. More specifically, ASEP provides predefined human error probability values, whereas THERP requires the analyst to calculate the human error probability. This in turn lowers the analysis accuracy to the advantage of the simplicity and ease of performing the analysis. It is to be noted that beyond open-ended performance shaping factors, the ASEP method explicitly accounts for stress, time, immediate response, and procedures. Additional points to be noted with respect to this method are as follows [12]:

- It can be counted as an atomistic method because of the level of proceduralized detail provided in it.
- Its format is not a worksheet or rubic but rather a checklist procedure.
- The application of lookup tables to perform calculations eliminates any ambiguity in probability assignments to events or in the overall error probability calculation.

All in all, ASEP is a nuclear specific tool, and it has been successfully applied in the nuclear power industrial sector.

5.4.6 Human Cognitive Reliability Model

HCR model/correlation is a method used in human reliability assessment to evaluate the human error occurrence probability during the completion of a specific task. The method was developed in the early 1980s, and this method is based on the premise that the likelihood of success or failure of an operator in a time-critical task is dependent on the cognitive process, used for making the critical decisions that determine the outcome [26, 27]. Three performance shaping factors (i.e. stress level, quality of operator/plant interface, and operator experience) also influence the average (median) time taken to carry out the task. By combining these three performance shaping factors enables "response time" curves to be calibrated and compared to the time available for performing the task.

With the aid of these curves, the involved analyst can then estimate the likelihood that an operator will take the proper measure, as indicated by a given stimulus (e.g. pressure warning signal), within the framework of available time window. The basis for the relationship between these normalized times and human error probabilities is the simulator experimental data.

Some of the main benefits and drawbacks of this method are as follows [24]:

Benefits

- It is quite quick method to perform and is easy to use.
- It explicitly models the time-dependent nature of human reliability assessment.

Drawbacks

- It is highly sensitive to changes in the estimate of the median time.
- It considers only three performance shaping factors.
- The human error probability generated by the method is not complete.

5.4.7 Standardized Plant Analysis Risk–Human Reliability Analysis

This method was developed at the Idaho National Laboratory to estimate the probability that an operator will fail when tasked with carrying out a basis event [12, 28]. The method does the following [14, 28]:

(1) Decomposes probability into contributions from action-related failures and diagnosis-related failures.
(2) Accounts for the context associated with human failure events with the aid of performance shaping factors and dependency assignment for adjusting a base-case human error probability
(3) Makes use of pre-defined and base-case human error probabilities and performance shaping factors along with guidance on how to assign the correct value of the performance shaping factor.
(4) Makes use of a beta distribution for uncertainty analysis.
(5) Makes use of designated worksheets for ensuring analyst consistency.

Furthermore, the method assigns human activity to one of two general task classifications: diagnosis or action. Diagnosis tasks consist of reliance on experience and knowledge to comprehend existing situations, determining proper courses of action, and planning prioritizing activities or actions. Some examples of action tasks are operating equipment, carrying out testing or calibration, and starting pumps/machines.

The eight performance shaping factors shown in Fig. 5.4 are accounted for in the quantification process of this method [6, 14, 28].

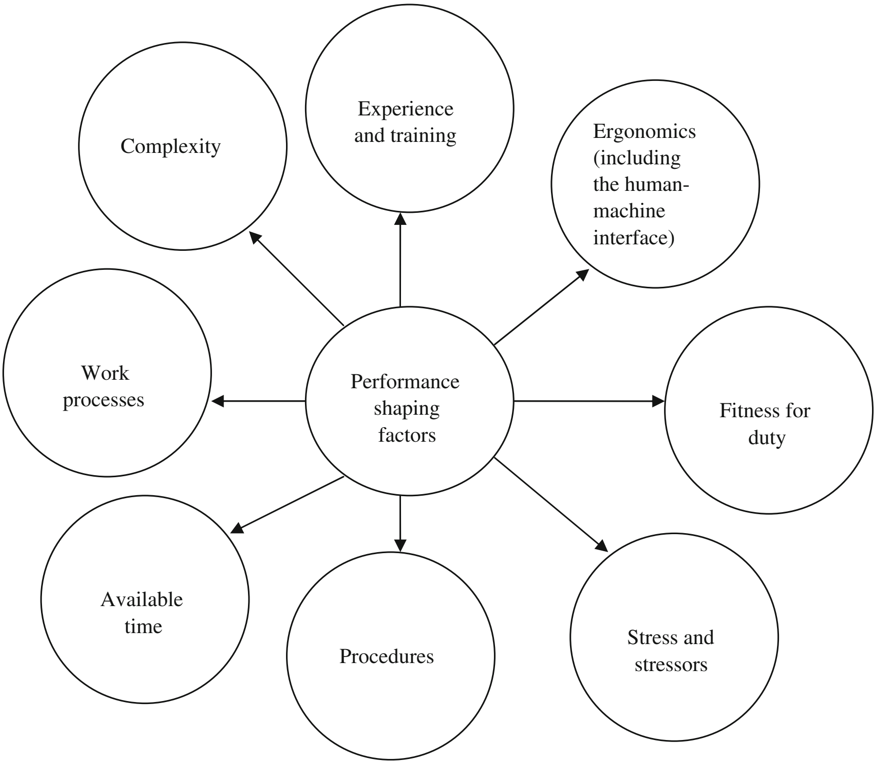


Fig. 5.4 Performance shaping factors considered in the quantification process of SPAR-H

A main element of this method is the SPAR-H worksheet, which significantly simplifies the estimation procedure. The worksheet using process varies slightly, depending on whether the analyst is using the method to conduct a more detailed HRA, perform event analysis, or build SPAR models.

Some of the benefits and drawbacks of this method are as follows [14, 29]:

Benefits

- The eight performance shaping factors included in the method cover many situations where more detailed analysis is necessary.
- A simple underlying model makes this method relatively straightforward to use, and final results are easily traceable.

Drawbacks

- The method may not be suitable in situations, where more detailed and realistic analysis of diagnosis errors is required.

- For detailed analysis, the degree of resolution of the performance shaping factors may be insufficient.

Additional information on this method is available in Ref. [28].

5.4.8 Human Error Assessment and Reduction Technique

This method is used in the area of human reliability assessment to evaluate the human error occurrence probability throughout the completion of a certain task. The method first appeared in 1986 and is widely used in the United Kingdom nuclear industry [14, 22, 30, 31]. The method is based on the following premises [14]:

- Basic human reliability depends on the generic nature of the task to be carried out.
- Under "perfect" situations, this level of reliability will tend to be achieved quite consistently with a specified nominal likelihood within probabilistic limits.
- Given that the perfect situations under all circumstances do not exist, the predicted human reliability may degrade as a function of the extent to which highlighted error producing situations might be applicable.

In this method, 9 generic task types are described, each with an associated nominal human error occurrence potential, and a total of 38 error generating conditions that may affect reliability of task, each with a maximum amount by which the nominal human error occurrence potential can be multiplied. The following three are the key elements of this method [14]:

(1) Categorize the task for analysis into any one of the generic task types as well as assign the nominal human error occurrence potential to that task.
(2) Make decision which error producing situations may affect reliability of task and then evaluate/consider the assessed proportion of affect for each and every error producing situation.
(3) Calculate human error occurrence potential of task.

Some of the benefits and drawbacks of this method are as follows [14, 22, 30, 31]:

Benefits

- It requires relatively limited resources for completing an assessment.
- It is a simple, quick, and versatile human reliability calculation approach, which also provides the user suggestions to reduce error.

Drawbacks

- It does not include error dependency modelling.
- It lacks information concerning the extent to which tasks should be decomposed to perform analysis.
- It needs greater clarity of description for assisting users when discriminating between generic tasks and their related error producing situations.

5.5 Problems

1. Discuss the issues concerning the incorporation of the HRA integrally into a PRA.
2. What are the HRA process steps in regard to nuclear power plants?
3. What are the information requirements of THERP, SLIM, HCR, and ASEP methods?
4. What were the main reasons for developing the ATHEANA method?
5. Compare CREAM and ATHEANA methods.
6. Describe the following two methods:
   - ASEP.
   - THERP.
7. What are the advantages and disadvantages of the following two methods?
   - HCR.
   - SPAR-H.
8. What is HEART? Describe it in detail?
9. Compare HEART and ATHEANA methods.
10. What are the benefits and drawbacks of the following two methods?
    - THERP.
    - CREAM.

References

1. Facts and Figures (2013) Nuclear industry association (NIA). Carlton House, London
2. U.S. Statistics, Institute for Energy Research (IER), Washington, DC, 2013
3. Ryan TG (1988) A task analysis-linked approach for integrating the human factor in reliability assessments of nuclear power plants. Reliab Eng Syst Saf 22:219–234
4. Trager TA (1985) Case study report on loss of safety system function events, Report No. AEOD/C504, U.S. Nuclear Regulatory Commission, Washington, DC, 1985
5. IEEE Guide for Incorporating Human Action Reliability Analysis for Nuclear Power Generating Stations, IEEE Std 1082–1997, Institute of Electrical and Electronics Engineers (IEEE), New York, 1997
6. Spurgin AJ, Lydell BOY (2002) Critique of current human reliability analysis methods. In: Proceedings of the IEEE seventh conference on human factors and power plants, pp 3.12–3.18
7. Strater O, Bubb H (1999) Assessment of human reliability based on evaluation of plant experience: requirements and implementation. Reliab Eng Syst Saf 63:199–219
8. Laux L, Plott C (2007) Using operator workload data to inform human reliability analyses. In: Proceedings of the joint 8th IEEE HFPP/13th HPRCT conference, pp 309–312
9. Kim IS (2001) Human reliability analysis in the man–machine interface design review. Ann Nucl Energy 28:1069–1081
10. Ryan TG (1988) A task analysis-linked approach for integrating the human factor in reliability assessments of nuclear power plants. Reliab Eng Syst Saf 22:219–234

11. Boring RL (2006) Modeling human reliability analysis using MIDAS. In: Proceedings of the 5th international topical meeting on nuclear plant instrumentation, controls, and human machine interface technology, pp 1270–1274
12. Boring RL, Gertman DI, Joe JC, Marble JL (2005) Human reliability analysis in the U.S. nuclear power industry: a comparison of atomistic and holistic methods. In: Proceedings of the human factors and ergonomics society 49th annual meeting, pp 1815–1819
13. Human Error Classification and Data Collection, Report No. IAEA.TECDOC 538, International Atomic Energy Agency (IAEA), Vienna, Austria, 1990
14. Bell J, Holroyd J (2009) Review of human reliability assessment methods, Report No. RR679, Health and Safety Laboratory, Buxton, UK, 2009
15. Cooper SE et al. (1996) A technique for human event analysis (ATHEANA)-technical basis and methodological description, Report No. NUREG/CR- 6350, U.S. Nuclear Regulatory Commission, Brookhaven National Laboratory, Upton, New York, April 1996
16. Technical Basis and Implementation Guide-lines for a Technique for Human Event Analysis (ATHEANA), Report No. NUREG-1624, U.S. Nuclear Regulatory Commission, Washington, DC, May 2000
17. Forester J et al (2004) Expert elicitation approach for performing ATHEANA quantification. Reliab Eng Syst Saf 83:207–220
18. Hollnagel E (1998) Cognitive reliability and error analysis method-CREAM. Elsevier Science, Oxford
19. Stanton NA, Salmon PM et al (2005) Human factors methods: a practical guide for engineering and design. Ashgate Publishing, Aldershot
20. Swain AD, Guttmann HE (1983) Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications, Report No. NUREG/CR- 1278, US Nuclear Regulatory Commission, Washington, DC, 1983
21. Kirwin B (1994) A guide to practical human reliability assessment. CRC Press, Boca Raton
22. Kirwan B et al (1997) The validation of three human reliability quantification techniques, THERP, HEART, and JHEDI: Part II-results of validation exercise. Appl Ergon 28(1):17–25
23. Embrey DE et al. (1984) SLIM-MAUD: an approach to assessing human error probabilities using unstructured expert judgement, volume I: overview of SLIM-MAUD, Report No. NUREG/CR-3518, US Nuclear Regulatory Commission, Washington, DC, 1984
24. Humphreys P (ed) (1995) Human reliability assessor's guide. AEA Technology, London
25. Swain AD (1987) Accident sequence evaluation program human reliability analysis procedure, Report No. NUREG/CR-4772, US Nuclear Regulatory Commission, Washington, DC, 1987
26. Hannaman GW, Spurgin AJ, Lukic YD (1984) Human cognitive reliability model for PRA analysis, Draft Report No. NUS-4531, EPRI Project No. RP2170-3, Electric Power and Research Institute, Palo Alto, California, 1984
27. Rasmussen J (1983) Skills, rules, knowledge, signals, signs, and symbols and other distinctions in human performance models. IEEE Trans Syst Man Cybern 13(3):257–266
28. Gertman D et al. (2004) The SPAR-H human reliability method, Report No. NUREG/CR-6883, US Nuclear Regulatory Commission, Washington, DC
29. Forester J et al. (2006) Evaluation of analysis methods against good practices, Report No. NUREG-1842, US Nuclear Regulatory Commission, Washington, DC, 2006
30. Kirwan B (1996) The validation of three human reliability quantification techniques, THERP, HEART, and JHEDI: part I-techniques descriptions and validation issues. Appl Ergon 27(6):359–373
31. Kirwan B et al (1997) The validation of three human reliability quantification techniques, THERP, HEART, and JHEDI: part III-practical aspects of the usage of the techniques. Appl Ergon 28(1):27–39

Chapter 6
Human Factors in Power Generation

6.1 Introduction

A modern large electrical power plant, powered by fossil fuels, hydro, nuclear energy, etc., may simply be called a complex human–machine system that controls a thermodynamic process employed for generating electricity. The machine aspect of the system is a rather sophisticated arrangement of software and hardware elements that are generally highly reliable and redundant. The human aspect of the system is a fairly large sociotechnological organization with engineering, management, training, operations, and maintenance manpower.

Needless to say, human factors play an important role in power generation. Although human factors became an important element in defence equipment design and development in the late 1950s and 1960s, in the area of power generation, it was not until the mid-1970s when the nuclear plants were designed using human factors analytical techniques or design standards [1]. More specifically, the nuclear power industrial sector used exactly the same engineering techniques that had been developed over the past five decades in designing fossil fuel and hydro power plants [1–3].

This chapter presents various important aspects of human factors, directly or indirectly, concerned with power generation.

6.2 Human Factors Engineering Design Goals and Responsibilities

There are many human factors engineering design goals with respect to power generation systems. Some of the main ones are as follows [4]:

- The plant design and allocation of all types of functions will clearly support operation vigilance and provide acceptable levels of workload (i.e. to minimize periods of operator overload and underload).

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_6,

- All personnel tasks can be performed within specified time and performance criteria.
- The operator interfaces will minimize operator-related errors and will clearly provide for error detection and recovery capability.
- The human–system interfaces, procedures, staffing/qualifications, training, and management and organizational support will clearly support a rather high degree of situation awareness.

The personnel responsible for human factors engineering within a power generation organization have many responsibilities. The important ones are as follows [4]:

- Developing human factors engineering-related procedures and plans.
- Verifying the implementation of team recommendations.
- Assuring that human factors engineering-related activities comply with the human factors engineering-related procedures and plans.
- Oversight and review of human factors engineering-related design, development, test, and evaluation-associated activities.
- Scheduling human factors engineering-related activities and milestones with respect to other modification activities.
- Initiation, recommendation, and provision of appropriate solutions through all designated channels for problems or difficulties highlighted during the implementation process of the human factors engineering-related activities.

6.3 Human Factors Issues in Ageing Power Plants

Humans play an important role in the effects of ageing on nuclear plants' safe and reliable operation. Thus, human factors issues may be more important than the issues concerned with component and materials degradation with age as human actions can decelerate or accelerate physical ageing of a power plant. These human factors issues can be categorized under six classifications as shown in Fig. 6.1 [5]. These classifications are management, maintenance, staffing, training, man–machine interface, and procedures.

As per past experiences [6], management impacts basically all facets of power plant performance including technical support, design, construction and modification, maintenance, and operations. There are many management-related issues that may arise in ageing power plants. Some of these, directly or indirectly, are difficulties in attracting and retaining good managers, lack of interest by top management, and tendency to delay decisions as long as possible [7].

Maintenance is another area which will impact and be impacted by ageing power plants. Some of the human factors-related issues belonging to this area are new maintenance staff may not be adequately trained in the technology that exists in ageing plants, loss in flexibility to transfer maintenance staff to other plants because of significant technological differences between old and new plants, and

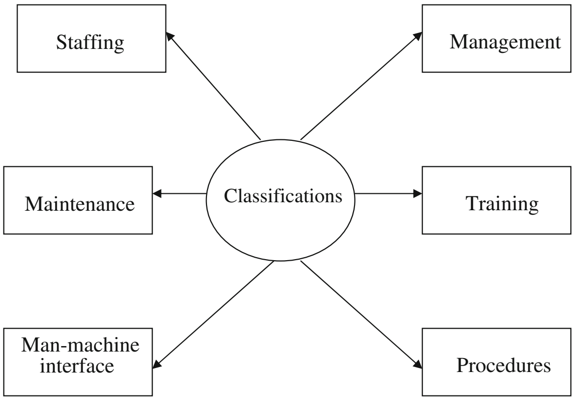


Fig. 6.1 Classifications of human factors issues in ageing nuclear power plants

increment in dose rates will make maintenance more difficult in certain areas of older plants [5]. Staffing-related issues in plant ageing are concerned with the ability to attract and retain good people for older power plants, particularly in areas such as operation and technical support.

The remaining three classification issues (i.e. training, man–machine interface, and procedures) are considered self-explanatory, but the information on these issued is available in Ref. [5].

6.4 Human Factors Issues that Can have Positive Impact on Nuclear Power Plant Decommissioning

Currently, there are around 435 nuclear reactors operating worldwide and about 57 of these reactors are in the process of decommissioning [8, 9]. It is estimated that the decommissioning of these reactors will cost billions of dollars to the world economy. For example, the estimated cost of decommissioning 19 reactors currently operating in the United Kingdom alone is over 70 billion pounds (i.e. over $100 billion dollars) [8].

Needless to say, much less is known or clearly understood regarding human factors that are crucial to, and can quite significantly affect, the success of the nuclear power plant decommissioning process [8, 10]. Nonetheless, some past experiences of decommissioning clearly indicate that, aside from technical challenges, there are many organizational and human factors that also need to be addressed with care [11, 12]. Four human factors issues that can have the most positive impact upon safe and successful decommissioning of power plants are shown in Fig. 6.2 [8].

Uncertainty about the future can affect decommissioning because of subsequent impact it can have on staff morale and motivation. Uncertainty to a certain degree is to be expected when decision is made to shut down and decommission a power

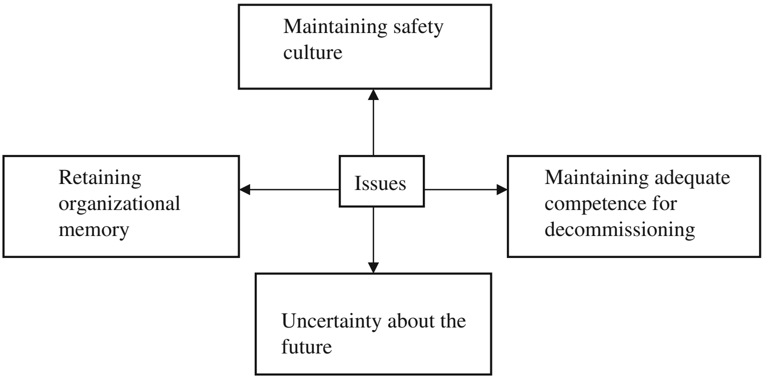


Fig. 6.2 Human factors issues that can have most positive impact upon safe and successful decommissioning of nuclear power plants

plant because to most plant staff members, decommissioning will be an entirely new phenomenon [8]. Furthermore, uncertainty can manifest itself in many different ways including reducing the involved staff morale, motivation, and commitment to the plant.

The most effective approach to manage uncertainty is reducing it to minimum [13]. This can be accomplished by developing an appropriate communication strategy whereby accurate and regular information is provided to all concerned staff members regarding future plans for decommissioning and the plant. It is to be noted that the communication process should be interactive to allow all concerned staff members to raise enquiries and have them properly resolved in a timely fashion. Furthermore, inviting key staff members to get involved in planning and preparing process for decommissioning can also be helpful to increase staff members' morale and "buy-in" to the overall process [14].

Maintaining adequate competence for decommissioning is another key human factors issue that can have the most significant impact upon safe and successful decommissioning and is composed of following three stages [8]:

- **Stage I**: This stage is concerned with initial decommissioning and includes defueling and removal of all non-fixed contaminated parts and readily removable equipment.
- **Stage II**: This stage is concerned with decontamination and dismantling of contaminated and other internal equipment.
- **Stage III**: This stage is concerned with demolition of those structures and buildings that are no longer needed.

Each of the above three stages will need different skills and knowledge of the power plant as well as of the technologies and tools to be employed and thus a different workforce profile. It simply means that during the entire decommissioning process, a significant training program will need to be developed to satisfy the training needs of managers, staff members, and involved contractors. Therefore, it is essential that appropriate training strategies are developed right at the planning stage so that required number of trainers are retained to develop and deliver training plans during the decommissioning process.

Safety culture is fundamental to the nuclear industrial sector, and the importance of its positive maintenance is an established element of daily regime of each and every nuclear power plant. Uncertainty and the loss of key staff members can have a profound impact on the safety culture of staff members left behind. As existing safety defences, processes, and procedures may no longer be effective, the following actions could be quite useful to maintain a positive safety culture during the decommissioning process [8, 11, 14, 15]:

- Re-evaluate safety culture indicators throughout the decommissioning process to reflect new and changing activities, environments, and risks as well as to ensure accurate measurement of safety culture.
- Provide feedback on performance to all involved workers on a regular basis to encourage morale and motivation and to highlight and raise awareness of possible risks.
- Emphasize the importance of workers' contribution with respect to safe and efficient decommissioning.
- Present decommissioning to all involved workers as a good opportunity for their future career development rather than a threat to their future employment.

Finally, in regard to "retaining organizational memory", human factors issue decommissioning requires accurate and clear knowledge of the plant history and operations including any modifications to the plant design. Most of this type of information can be retrieved from the plant documentation such as drawings, procedures, and event reports. Thus, it is very important to perform a documentation audit as soon as possible to find out what documentation is available and the accuracy of the information contained in the documentation. This type of information should be catalogued and stored in such a way so that it is easily accessible to all concerned personnel.

The knowledge held by experienced staff personnel may not have been documented through any formal processes or procedures. Because of uncertainty about the future, there is a considerable risk of losing these key personnel in the initial stages of planning for decommissioning. Therefore, it is very important, as soon as possible prior to the closure of the plant, to identify key roles for decommissioning and to develop relevant strategies to retain the key staff personnel for these roles. An example of these strategies is raising the profile of the role for making it more attractive, providing job security for a time period or even employing these key personnel on a part-time basis.

Additional information on the above four human factors issues is available in Ref. [8].

6.5 Human Factors Review Guide for Next-Generation Reactors and Guidance Documents for Human Factors

In 1994, the United States Nuclear Regulatory Commission (NRC) developed a document (NUREG-0711) entitled "Human Factors Engineering Program Review Model" [16] to basically serve as a human factors guide for next generation of reactors [17]. The document described background, objective, applicant submittals, and review criteria for the ten human factors engineering elements shown in Fig. 6.3 [17].

The following inputs are considered useful with respect to each of the human factors engineering elements shown in Fig. 6.3 [17]:

Human Factors Engineering Program Management

- All applicants should submit the appropriate human factors engineering program plan for review by the concerned regulatory institutes.
- Human factors engineering-related tasks, organization, and relationships among these tasks should be reviewed with care.
- As human factors engineering issue tracking is a very important task in the human factors engineering program, issue selection criteria, issue management and handling procedures, and issue analysis approaches must be described in appropriate detail.

Operating Experience Review

- Important issues in the operation of earlier power plants must be analysed with care, and the results must be reflected in the design under consideration.
- As near-miss cases can provide information as important as that of plant events, it is considered essential to include the analysis of near-miss cases into the operating experience review.

Functional Requirement Analysis and Function Allocation

- Ensure that functional requirement analysis is performed to the level with which function allocation can be performed effectively.
- In addition to identifying functions important to safety, other general functions should also be included in the analysis to reflect the results of functional requirement analysis to the design.

Task Analysis

- Ensure that documentation clearly shows all types of relationships between task analysis and functional requirement analysis and function allocation results.
- Consider seriously, during the task analysis process, the tasks expected to face changes.

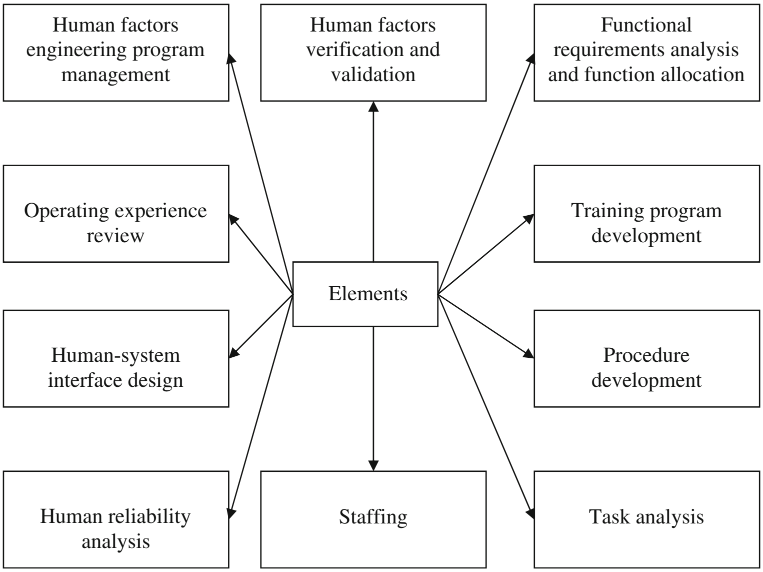


Fig. 6.3 Ten human factors engineering elements

Procedure Development

- Ensure that interface with other information displays and controls is quite efficient to enhance operator performance and not to induce human errors.
- Ensure that guidelines for modification, management, and validation of procedures are developed when using computerized procedures.

Human–System Interface Design

- Perform human–system interface evaluation independent of the human factors verification and validation.
- Ensure that the task analysis results are clearly reflected in human–system interface designs.

Human Factors Verification and Validation

- Make use of the United States NRC document entitled "Integrated System Validation: Methodology and Review Criteria" [18] for this element.

Human Reliability Analysis

- Ensure that a clear definition of data input–output between the human factors engineering design team and probabilistic risk analysis team is properly described.

- Ensure that the design-related data from probabilistic risk analysis required by the human factors engineering design team are properly identified and interactions between probabilistic risk analysis team and the human factors engineering design team are clearly described.

Training Program Development

- Ensure that all types of training requirements are clearly identified during the design phase.

Staffing

- Because of the changes in human–system interface design and resulting personnel tasks, ensure that staffing analysis is performed with care.

6.5.1 Guidance Documents for Human Factors

There are many guidance documents for human factors that can, directly or indirectly, be used in the area of power generation. Three of these documents produced by the United States NRC to ensure that personnel performance and reliability are appropriately supported in nuclear power plants are NUREG-0800, NUREG-0711, and NUREG-0700 [19]. NUREG-0800 provides a high-level review framework for performing human factors engineering reviews [20]. The updated versions (i.e. Rev. 1 and Rev. 2) of NUREG-0711 and NUREG-0700, respectively, are described below, separately [19].

NUREG-0711 (Rev. 1)
The original version of this document was described earlier. This version addresses both new control room designs and control room modernization issues. In addition, the version includes two more human factors engineering review elements. More specifically, two more elements in addition to the ten elements are shown in Fig. 6.3. The new elements are human performance monitoring and design implementation.

Human performance monitoring is concerned with providing guidance to assure that a human performance monitoring strategy is in place so that no major safety-related degradation occurs when changes are made in the plant as well as providing proper assurance that all conclusions drawn from the evaluation remain valid over time period. Design implementation is concerned with addressing the manner in which changes are carried out to control rooms and human–system interfaces. Furthermore, the guidance particularly focuses on review of the implementation of all plant changes so that their resulting effects on personnel performance are considered properly.

Some of the human factors engineering elements in Fig. 6.3 that have changed quite significantly in this version are as follows [19]:

- Human–system interface design.
- Human factors verification and validation.
- Functional requirements analysis and allocation.
- Human reliability analysis.

NUREG-0700 (Rev. 2)
The first version of this document (i.e. NUREG-0700) provides the guidelines for reviewing the human factors engineering aspects of human–system interface technology such as control room design, information systems, controls, and alarms [19]. The first revision of this document (i.e. NUREG-0700, Rev. 1) [20] addressed the "gaps" in the criteria. The second revision of the document (i.e. NUREG-0700, Rev. 2) has changed quite considerably from the first revision (i.e. NUREG-0700, Rev. 1) because human–system interface characterizations have been added to each major section. A characterization may simply be described as a description of the functions and characteristics of the human–system interface topic area that is crucial to human performance.

Nonetheless, the new guidance addresses the eight different aspects of human–system interface design shown in Fig. 6.4 [19]. The human factors engineering guidelines in the guidance are divided into four basic parts as follows [19]:

- **Part I** This part contains guidelines for three basic human–system interface elements: controls, information displays, and user–interface interaction and management. In turn, the elements are utilized as building blocks for developing human–system interface systems to serve certain functions.
- **Part II** This part contains the guidelines to review soft control system, alarm system, communication system, safety function and parameter monitoring system, computerized operator support system, group-view display system, and computer-based procedure system.
- **Part III** This part contains guidelines for reviewing workstations and workplaces. Workstations, including panels and consoles, are locations where human–system interfaces are integrated together for providing an area where plant staff/personnel can carry out their assigned tasks. Furthermore, workstations are situated at workplaces such as remote shutdown facilities and the main control room.
- **Part IV** This part contains guidelines for reviewing the human–system interface support, i.e. maintaining digital systems.

Additional information on NUREG-0700, Rev. 2, is available in Ref. [19].

6.6 Potential Human Factors Engineering Application Areas and Expected Problems

Some of the potential human factors engineering application areas with respect to power generation are as follows [21]:

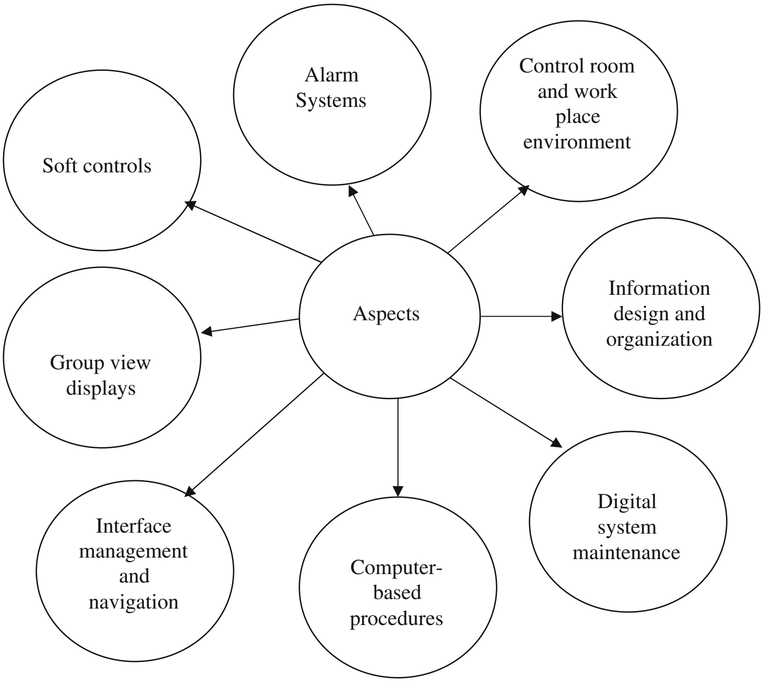


Fig. 6.4 The aspects of human–system interface design addressed by the document: NUREG-0700, Rev. 2

- Greater application of human factors engineering principles to operations and maintenance of non-nuclear power plants.
- Assessing and understanding organizational factors' influence on safety.
- Extension of all successful human–system interface programs and technologies to human–system interfaces out in the power plant (i.e. outside the power plant's control room).
- Assessing and understanding deregulation's influence on safety.
- Focus on crew and individual performance assessment as well as on unplanned and unexpected events' management.
- Improving data collection and analysis approaches, including event reporting and human reliability analysis.
- Assessing and understanding decommissioning's human factors engineering aspects.
- Improvement of operations and maintenance design.

Some of the human factors engineering application-related problems in the area of power generation to be faced and overcome are as follows [21]:

- Lack of proper standardization in the methodology and application of human factors analytical procedures such as task analysis, function allocations, human reliability analysis, and functional requirements used during the design and development process/phase.

- Tendency to focus intensively on human factors after the occurrence of near disaster or catastrophe.
- Tendency of some power industry management personnel to regard the necessity for human factors in terms of a temporary “magic bullet” to be used, primarily after the occurrence of a serious problem, rather than establishing proper systematic mechanisms to address such concerns in terms of constant proper preventive measures.
- Difficulty in recruiting and training resources and top talent in the area of human factors because some people consider nuclear power, particularly in North America, to be a dying industry.

6.7 Problems

1. Write an essay on human factors in power generation with emphasis on historical developments.
2. List at least five important responsibilities of personnel responsible for human factors engineering within a power generation organization.
3. Discuss human factors issues in ageing power plants.
4. Discuss human factors issues that can have most positive impact upon safe and successful decommissioning of nuclear power plants.
5. What are the actions that could be useful to maintain a positive safety culture during the power plant decommissioning process?
6. What are the ten human factors engineering elements in the United States NRC document: NUREG-0711?
7. Describe the United States NRC document: NUREG-0700 (Rev. 2).
8. What are the potential human factors engineering application areas with respect to power generation?
9. What are the human factors engineering application-related problems in the area of power generation to be faced and overcome?
10. Describe the United States NRC document: NUREG-0711 (Rev. 1).

References

1. Parsons SD, Seminara JL (2000) Power systems human factors/ergonomics activities in the United States. In: Proceedings of the IEA/HFEA Congress, pp 3.807–3.810
2. Parsons SO, Eckert SK, Seminara JL (1978) Human factors design practices for nuclear power plant control rooms. In: Proceedings of the human factors society annual meeting, pp 133–139

3. Seminara JL, Parsons SO (1980) Survey of control-room design practices with respect to human factors engineering. Nucl Saf 21(5):603–617
4. Hill D, Alvarado R, Heinz M, Fink B, Naser J (2004) Integration of human factors engineering into the design change process. In: Proceedings of the American nuclear society international topical meeting on nuclear plant instrumentation, controls, and human–machine interface technologies, pp 1–10
5. Widrig RD (1985) Human factors: a major issue in plant aging. In: Proceedings of the international conference on nuclear power plant aging, availability factor, and reliability, pp 65–68
6. Osborn R et al (1983) Organizational analysis and safety for utilities with nuclear power plants. Report No. NUREG/CR-3215, United States Nuclear Regulatory Commission, Washington, D.C
7. Child J, Kieser A (1981) Development of organizations overtime. In: Nystrom P, Starbuck W (eds) Handbook of organizational design. Oxford University Press, New York, pp 28–64
8. Blackett C (2008) The role of human factors in planning for nuclear power plant decommissioning. In: Proceedings of the 3rd IET international conference on system safety, pp 1–6
9. "Nuclear power reactors in the world". IAEA 2007 Edition, International Atomic Energy Agency (IAEA), Vienna, Austria, June 2007
10. "Organization and management for decommissioning of large nuclear facilities". IAEA Technical Reports Series No. 399, International Atomic Energy Agency (IAEA), Vienna, Austria, December 2000
11. "Planning, managing, and organizing the decommissioning of nuclear facilities: lessons learned". Report No. IAEA-TECDOC-1394, International Atomic Energy Agency, Vienna, Austria, May 2004
12. Durbin NE, Melber B, Lekberg A (2001) Decommissioning: regulatory activities and identification of key organizational and human factors safety issues. SKI Report No. 01:43, Swedish Nuclear Power Inspectorate, Stockholm, Sweden, Dec 2001
13. Durbin NE, Lekberg A, Melber BD (2001) Potential effects of organizational uncertainty on safety. SKI Report No. 01:42, Swedish Nuclear Power Inspectorate, Stockholm, Sweden, Dec 2001
14. "Managing change in nuclear facilities". Report No. IAEA-TECDOC-1226, International Atomic Energy Agency (IAEA), Vienna, Austria, July 2001
15. "Managing the socio economic impact of the decommissioning of nuclear facilities". IAEA Technical Reports Series No. 464, International Atomic Energy Agency, Vienna, Austria, April 2008
16. "Human factors engineering program review model". Report No. NUREG-0711. U.S. Nuclear Regulatory Commission, Washington, D.C (1994)
17. Lee JW et al (1999) Human factors review guide for Korean next generation reactor, Transactions of the 15th conference on structural mechanics in reactor technology, pp XI-353–XI-360
18. O'Hara J, Stubler J, Higgins J, Brown W (1997) Integrated system validation: methodology and review criteria. Report No. NUREG/CR-6393, U.S. Nuclear Regulatory Commission, Washington, D.C
19. O'Hara JM et al (2002) Updating the NRC's guidance for human factors engineering reviews. In: Proceedings of the IEEE 7th human factors meeting, pp 4.22–4.27
20. "Standard review plan". Report No. NUREG-0800, U.S. Nuclear Regulatory Commission, Washington, D.C., 1996
21. Parsons SO, Seminara JL, O'Hara JM (2000) Power systems human factors/ergonomics activities in the United States. In: Proceedings of the IEA/HFES Congress, pp 3-807–3-810

Chapter 7
Human Error in Power Generation

7.1 Introduction

Generally, good design, through sound quality assurance, installation, and operation and maintenance programs provide the basic foundation for power plants' safe and reliable operations. Nonetheless, humans play an important role during design, production, operation, and maintenance phases of systems used in power plants. Although the degree of role of humans may vary quite considerably from one phase to another, their interactions are subject to deterioration because of the occurrence of human error.

A study performed by one utility indicates that failures occurring due to human error were roughly two and a half times higher than those attributed to hardware failures [1]. The occurrence of human error in power generation can be quite catastrophic. Two examples are the Three Mile Island and Chernobyl nuclear power station accidents in the United States and Ukraine, respectively. Both these accidents that occurred on March 28, 1979, and on April 26, 1986, respectively, were, directly or indirectly, the result of human error [2].

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

7.2 Facts, Figures, and Examples

Some of the facts, figures, and examples directly or indirectly concerned with the occurrence of human error in power generation are as follows:

- During the period 1990–1994, around 27 % of the commercial nuclear power plant outages in the United States were the result of human error [1].
- As per Ref. [3], a study by the United States Nuclear Regulatory Commission (NRC) of Licensee Event Reports reported that around 65 % of nuclear system failures involve human error [4].

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*,
Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_7,

- As per Ref. [5], during the period 1969–1986, 54 % of the incidents due to human errors in Japan resulted in automatic shutdown of nuclear reactors and 15 % of that resulted in power reduction.
- As per Refs. [6, 7], about 70 % of nuclear power plant operation errors appear to have a human factors origin.
- A study of 255 shutdowns that occurred in Korean nuclear power plants during the period 1978–1992 reported that 77 of these shutdowns were human-induced [8, 9].
- As per Ref. [2], in 1979, Three Mile Island nuclear power plant accident in the United States was the result of human-related problems.
- In 1986, Chernobyl nuclear power plant accident in Ukraine, widely regarded as the worst accident in the history of nuclear power, was also the result of human-related problems [2].
- A study of 143 occurrences of operating US commercial nuclear power plants during the period from February 1975 to April 1975, revealed that about 20 % of the occurrences were due to operator errors [10, 11].
- As per Ref. [12], the major incident/accident reports of nuclear power plants in Korea indicate that about 20 % of the total events occur due to human error.
- As per Refs. [6, 13], operation error associated with control centres in fossil-fired steam generating power plants in the United States could result in upto 3.85 % of plants' unavailability.

7.3 Major Factors for Human Errors and Their Occurrence Preventions

There are many major factors for the occurrence of human errors/accidents in the industrial sector including power generation. Eleven of these major factors along with their corresponding preventive measures with respect to an individual (in parentheses) are as follows [14–16]:

- **Performing tasks too fast** (Avoid operating equipment when you are tense, tired, or do not feel well).
- **Taking chances and high risks** (Avoid "showing off" or thinking that an accident cannot occur).
- **Faulty equipment** (Check equipment on regular basis).
- **Sleeplessness and fatigue** (Take breaks as considered appropriate to prevent fatigue).
- **Extreme cold or heat** (Perform inside tasks/jobs or minimize exposure to extreme temperatures as much as possible).
- **Poor skill** (Read instruction manuals with care and get some skilled individual in the area to help you).
- **Medication, drugs, and alcohol** (Avoid operating equipment/machines or performing dangerous tasks if you are on some form of drugs, taking medication, or have been drinking).

- **Panic in an emergency situation** (Learn first aid so you know exactly what action to take).
- **Let-down from low blood sugar and hunger** (Take fructose tablets or eat appropriate snacks to fight let-down).
- **Emotional upsets and anger** (Take time to calm down to normal level).
- **Daydreaming and not concentrating** (Vary routine to fight monotony as appropriate).

7.4 Occurrences Caused by Operator Errors During Operation and Operator Error Causes

Over the years, there have been many occurrences in commercial nuclear power plants caused by operator errors during operation. Some of these occurrences are as follows [10, 11, 17–19]:

- Reactor mode switch in incorrect mode.
- Suppression chamber water volume goes over the limit.
- Control rod inserted well beyond limit.
- Control rod not declared non-functional or inoperable when misaligned.
- Serious judgement error in monitoring.
- Reactor coolant system leakage evaluation not performed.
- A power board inadvertent trip.
- Process vent gaseous radiation monitor left in calibrate mode.
- Two adjacent control blades withdrawn during the rod driver overhaul process.
- Steam generator blow-down function not monitored at all.
- Sudden release of low-level radioactive water.
- Concentrated boric acid storage tank well below limits.

Some causes of operator errors that resulted in occurrences such as above are shown in Fig. 7.1 [11].

Additional information on the above occurrences and the causes of operator errors is available in Ref. [11].

7.5 Questions to Measure Up Electrical Power System Operating Practices to Reduce Human Errors

Over the years, in the area of electric power systems, various types of failures have occurred due to human errors. Two examples of such failures are as follows [20]:

- An electrician assigned to carry out modification to the boiler control circuit when one of the power plant's two steam boilers was down for annual inspection

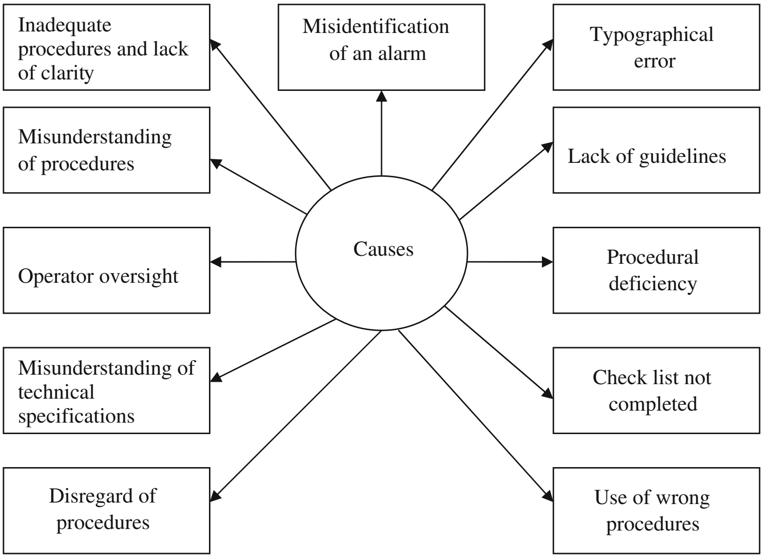


Fig. 7.1 Some causes of operator errors that resulted in occurrences in commercial nuclear power plants

and maintenance erroneously started to work on the control circuit of the operating boiler and shut down the operating boiler.
- After a severe thunderstorm, the shift supervisor of a power plant carried out a walk-through inspection of primary distribution switch gear of the power plant. After seeing a red light for each circuit breaker and erroneously thinking that the red light means "open" tripped each and every circuit breaker for obtaining a green-light indication. His action resulted in the shut down of the entire power plant.

The following six questions are considered most useful to measure up electrical power system operating practices to reduce human errors [20]:

- **Question No. 1**. Are all switching-related operations planned and reviewed with care well in advance and do they provide a clear logical step-by-step sequence that gives particular attention to all types of vulnerable situations?
- **Question No. 2**. Do you have an effective program to assure that items such as system drawings, plant procedures, and vendor manuals are effectively filed and kept up to date?
- **Question No. 3**. Is the split in responsibilities between the utilization system and distribution system clearly understood and defined effectively?
- **Question No. 4**. Are the long-range and day-to-day functions coordinated under a highly knowledgeable power system "expert" and do shift and pack up personnel clearly understand their assigned responsibilities and are they properly trained?

- **Question No. 5**. Do you have a proper procedure for assuring that all involved equipment is clearly identified with unique and clearly located identification and that field identification clearly agrees with drawings and all other concerned documentation?
- **Question No. 6**. Are proper steps taken for assuring that all types of redundant or adjacent systems are not accidentally turned on/operated?

7.6 Performance Shaping Factors

Performance shaping factors may simply be described as the factors that encompass those influences that degrade or enhance human performance. In human reliability analysis methods, performance shaping factors are used to highlight human error contributors as well as to provide a basis to quantify those contributors systematically.

Nonetheless, performance shaping factors may be classified under two categories: direct and indirect [21]. The direct performance shaping factors are those factors that can be measured directly, whereby there is a one-to-one relationship between the magnitude of the performance shaping factor and that which is measured. The indirect performance shaping factors are those performance shaping factors that cannot be measured directly, whereby the magnitude of the performance shaping factor can only be measured subjectively or multi-variately. The common direct/indirect performance shaping factors are as follows [21, 22]:

- Procedures
- Complexity
- Accessibility and equipment operability
- Experience and training
- Need for special tools
- Time available
- Ergonomic quality of human–system interface
- Availability of instrumentation
- Available staffing and resources
- Special fitness needs
- Workload, time pressure, and stress
- Communications
- Environment
- Consideration of realistic accident sequence diversions and deviations
- Team/crew dynamics.

Important direct/indirect performance shaping factors in nuclear power plant operations are shown in Fig. 7.2 [23].

Additional information on all of the above performance shaping factors is available in Refs. [21, 23].

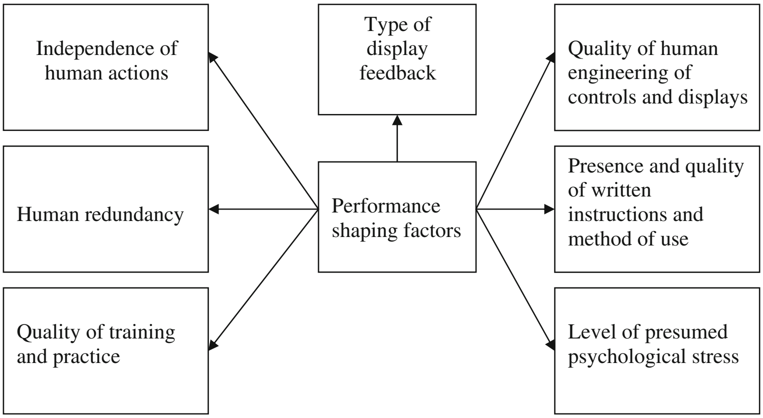


Fig. 7.2 Important direct/indirect performance shaping factors in nuclear power plant operations

7.7 Methods for Analyzing Human Errors in Power Generation

Over the years, many methods have been developed in the areas of safety, reliability, and quality to perform various types of analysis. Some of these methods can also be used to perform human error analysis in power generation. Three of these methods are presented below.

7.7.1 Pontecorvo Method

This method can be used to obtain reliability estimates of task performance by a person in the area of power generation. The method initially obtains reliability estimates for discrete and separate subtasks with no accurate reliability figures, and then, it combines these very estimates for obtaining the overall task reliability. Generally, this method is used during initial design phases to quantitatively assess the interaction of humans and machines. The method can also be used to determine the performance of a single person acting alone.

Pontecorvo method is composed of six steps shown in Fig. 7.3 [24, 25]. Step 1 is concerned with identifying the tasks to be performed. These tasks should be identified at a gross level (i.e. one complete operation is to be represented by each task). Step 2 is concerned with the identification of those subtasks of each task that are essential for its completion. Step 3 is concerned with collecting empirical performance-related data from sources such as experimental literature and in-house operations. These data should be subject to those types of environments under which subtasks are to be performed.

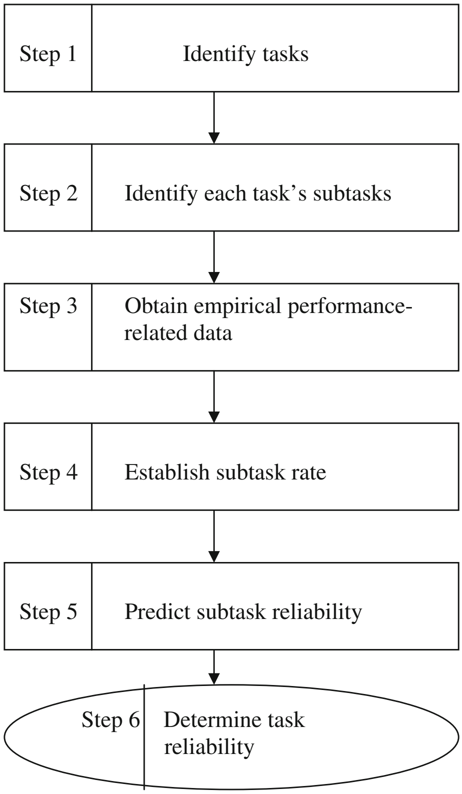


Fig. 7.3 Steps of Pontecorvo method

Step 4 is concerned with rating each subtask according to its level of perceived difficulty or potential for the occurrence of error. Usually, a 10-point scale is used for judging the appropriate subtask rate. The scale varies from least error to most error. Step 5 is concerned with predicting subtask reliability and is accomplished by expressing the data's judged ratings and the empirical data in the form of straight line. For goodness of fit, the regression line is tested.

Finally, Step 6 is concerned with determining the task reliability, which is obtained by multiplying subtasks' reliabilities.

It is to be noted that the above-described approach is used for estimating the performance of a single person acting alone. However, in a situation when a back person is available, the probability of the task being performed correctly (i.e. the task reliability) would be higher. Nonetheless, the backup person may not be available all of the time. In such a situation, the overall reliability of two persons working together to perform a given task can be estimated by using the following equation [24, 25]:

$$R_{\text{ov}} = \left[\left\{1 - (1 - R)^2\right\}T_a + RT_u\right] / (T_a + T_u) \quad (7.1)$$

where

R_{ov} is the overall reliability of two persons working together to perform a task
R is the reliability of the single person
T_u is the percentage of time the backup individual is unavailable
T_a is the percentage of time the backup individual is available.

Example 7.1 Two workers are working together independently in the area of power generation to perform an operation-related task. The reliability of each worker is 0.95, and the backup worker is available around 60 % of the time. In other words, 40 % of the time, the backup worker is not available.

Calculate the reliability of performing the operation-related task correctly. By substituting the given data values into Eq. (7.1), we get

$$\begin{aligned} R_{ov} &= \left[\left\{1-(1-0.95)^2\right\}(0.60)+(0.95)(0.40)\right]/(0.6+0.4) \\ &= 0.9785 \end{aligned}$$

Thus, the reliability of performing the operation-related task correctly is 0.9785.

7.7.2 Probability Tree Method

This is another method that can also be used to perform human error analysis in power generation [26]. The method is concerned with representing human actions and other events associated with the system diagrammatically. Thus, diagrammatic task analysis is denoted by the branches of the probability tree. More specifically, the branching limbs of the tree represent outcomes (i.e. success or failure) of each action or event associated with a given problem. Furthermore, each branch of the tree is assigned an occurrence probability.

Some of the advantages of the probability tree method are as follows [24]:

- It serves as a visibility tool.
- It is helpful to decrease the error occurrence probability due to computation because of computational simplification.
- It can incorporate, with some modifications, factors such as emotional stress, interaction effects, and interaction stress.
- It is quite useful in applying predictions of individual error rates as well as predicts the quantitative effects of errors.

The application of this method in the area of human error in power generation is demonstrated through the following example.

Example 7.2 Assume that a task of nuclear power station control room operator is composed of two independent subtasks, say, x and y. Each of these two subtasks

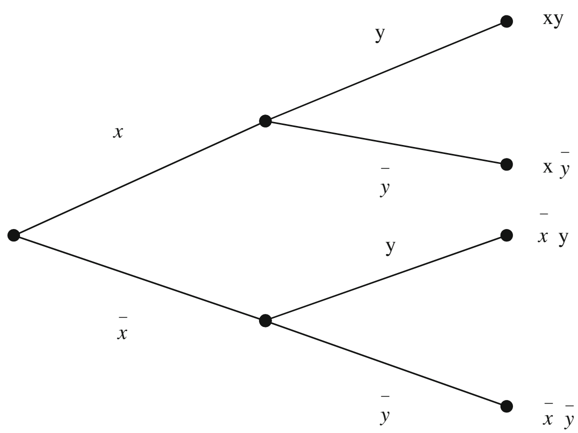


Fig. 7.4 Probability tree for the nuclear power station control room operator performing tasks x and y

can be performed either correctly or incorrectly, and subtask x is performed before subtask y.

Develop a probability tree for the example and obtain probability expressions for the following:

1. Successfully accomplishing the task by the control room operator.
2. Not successfully accomplishing the task by the control room operator.

In this case, the control room operator first carries out subtask x correctly or incorrectly and then proceeds to carrying out subtask y. This complete scenario is denoted by the Fig. 7.4 probability tree diagram.

The four letter symbols used in Fig. 7.4 are defined below.

x denotes the event that subtask x is performed correctly by the control room operator.

$\bar{x}$ denotes the event that subtask x is performed incorrectly by the control room operator.

y denotes the event that subtask y is performed correctly by the control room operator.

$\bar{y}$ denotes the event that subtask y is performed incorrectly by the control room operator.

By examining the Fig. 7.4, it can be noted that there are three distinct possibilities (i.e. $x\bar{y}, \bar{x}y$, and $\bar{x}\bar{y}$) for not successfully accomplishing the task by the nuclear power station control room operator. Thus, the probability of not successfully accomplishing the task by the control room operator is given by

$$\begin{aligned} P_{\mathrm{tf}} &= P(x\bar{y} + \bar{x}y + \bar{x}\bar{y}) \\ &= P_x P_{\bar{y}} + P_{\bar{x}} P_y + P_{\bar{x}} P_{\bar{y}} \end{aligned} \tag{7.2}$$

where

P_x is the probability of performing subtask x correctly by the control room operator

$P_{\bar{y}}$ is the probability of performing subtask y incorrectly by the control room operator

$P_{\bar{x}}$ is the probability of performing subtask x incorrectly by the control room operator

P_y is the probability of performing subtask y correctly by the control room operator

P_{tf} is the probability of not successfully accomplishing the task by the control room operator.

Since $P_{\bar{x}} = 1 - P_x$ and $P_{\bar{y}} = 1 - P_y$, Eq. (7.2) reduces to

$$\begin{aligned} P_{\mathrm{tf}} &= P_x\left(1 - P_y\right) + (1 - P_x)P_y + (1 - P_x)\left(1 - P_y\right) \\ &= 1 - P_x P_y \end{aligned} \tag{7.3}$$

Similarly, by examining Fig. 7.4, it can be concluded that there is only one possibility (i.e. xy) for successfully accomplishing the task by the control room operator. Thus, the probability of successfully accomplishing the task by the control room operator is expressed by

$$\begin{aligned} P_{ts} &= P(xy) \\ &= P_x P_y \end{aligned} \tag{7.4}$$

where

P_{ts} is the probability of successfully accomplishing the task by the nuclear power station control room operator.

Example 7.3 Assume that in Example 7.2, the probabilities of the nuclear power station control room operator carrying out subtasks x and y correctly are 0.97 and 0.85, respectively. Calculate the probability of failure of the control room operator to accomplish the task successfully.

By inserting the specified data values into Eq. (7.3), we obtain

$$\begin{aligned} P_{tf} &= 1 - (0.97)(0.85) \\ &= 0.1755 \end{aligned}$$

Thus, the probability of failure of the control room operator to accomplish the task successfully is 0.1755.

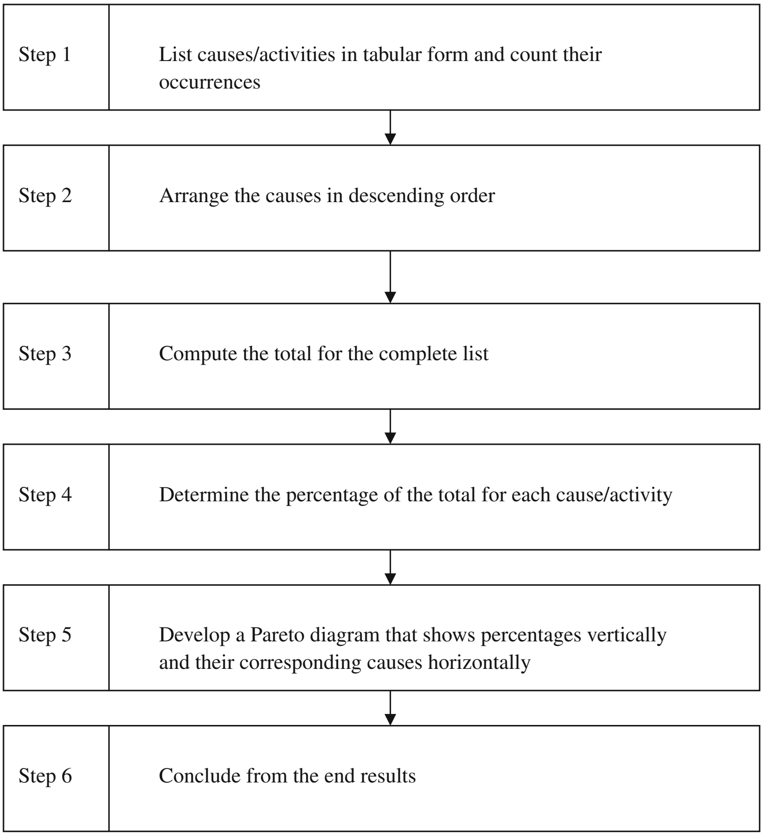


Fig. 7.5 Pareto analysis steps

7.7.3 Pareto Analysis

This is a quite useful method that can be used to separate the important causes of human error-related problems in the area of power generation from the trivial ones. The method is named after its founder Vilfredo Pareto (1848–1923), an Italian economist.

In the area of power generation, Pareto analysis is considered a powerful tool to identify areas for concerted effort to eliminate or minimize errors.

The method is composed of six steps shown in Fig. 7.5 [27, 28]. Additional information on this method is available in Refs. [26–29].

7.8 Problems

1. List at least eight facts, figures, and examples concerned with human error in power generation.
2. List at least ten occurrences in commercial nuclear power plants caused by operator errors during operation.
3. What were the causes of operator errors that resulted in occurrences in commercial nuclear power plants?
4. What are the six questions considered most useful to measure up electrical power system operating practices?
5. List at least 15 common direct/indirect performance shaping factors.
6. What are the important direct/indirect performance shaping factors in nuclear power plant operations?
7. Describe Pontecorvo method.
8. What are the advantages of the probability tree method?
9. Assume that a task of a nuclear power station control room operator is composed of three independent subtasks, say, x, y, and z. Each of these subtasks can be either performed correctly or incorrectly, and subtask x is performed before subtask y, and subtask y is accomplished before subtask z. Develop a probability tree and obtain a probability expression for performing the overall task incorrectly by the control room operator.
10. What is Pareto analysis? Describe it in detail.

References

1. Varma V (1996) Maintenance training reduces human errors. Power Eng 98:44–47
2. Kawano R (1997) Steps toward the realization of human-centered systems: an overview of the human factors activities at TEPCO. In: Proceedings of the IEEE sixth annual human factors meeting, pp 13.27–13.32
3. Ryan GT (1988) A task analysis-linked approach for integrating the human factor in reliability assessments of nuclear power plants. Reliab Eng Syst Saf 22:219–234
4. Trager TA Jr (1985) Case study report on loss of safety system function events. Report No. AEOD/C504, United States Nuclear Regulatory Commission, Washington, D.C
5. Mishima S (1988) Human factors research program: long term plan in cooperation with government and private research centers. In: Proceedings of the IEEE conference on human factors and power plants, pp 50–54
6. Williams JC (1988) A data-based method for assessing and reducing human error to improve operational performance. In: Proceedings of the IEEE conference on human factors and power plants, pp 436–450
7. An Analysis of Root Causes in 1983 and 1984 Significant Event Reports (1985) Report No. 85-027, Institute of Nuclear Power Operations, Atlanta, Georgia, July 1985
8. Heo G, Park J (2010) A framework for evaluating the effects of maintenance-related human errors in nuclear power plants. Reliab Eng Syst Saf 95:797–805
9. Lee JW, Park GO, Park JC, Sim BS (1996) Analysis of human error trip cases in Korean NPPs. J Korean Nucl Soc 28:563–575

10. Scott RL (1975) Recent occurrences of nuclear reactors and their causes. Nucl Saf 16:496–497
11. Husseiny AA, Sabry ZA (1980) Analysis of human factor in operation of nuclear power plants. Atomkernenergie Kerntechnik 36:115–121
12. Kim J, Park J, Jung W, Kim JT (2009) Characteristics of test and maintenance human errors leading to unplanned reactor trips in nuclear power plants. Nucl Eng Des 239:2530–2536
13. Oliver JA, Baker JE, Roth JW (1981) Assessment of the use of human factors in the design of fossil-fired steam generating system. EPRI Report No. CS-1760, Electric Power Research Institute, Palo Alto, California
14. Koval DO, Floyd HL II (1998) Human element factors affecting reliability and safety. IEEE Trans Ind Appl 34(2):406–414
15. McCornack RL (1961) Inspector accuracy: a study of the literature. Report No. SCTM 53-61 (14), Sandia Corporation, Albuquerque, New Mexico
16. Etemadi AH, Fotuhi-Firuzabad M (2008) Quantitative assessment of protection system reliability incorporating human errors. J Risk Reliab 9:255–263
17. Scott RL (1975) Recent occurrences of nuclear reactors and their causes. Nucl Saf 16:619–621
18. Thompson D (1974) Summary of recent abnormal occurrences at power-reactor facilities. Nucl Saf 15:198–320
19. Casto WR (1974) Recent occurrences of nuclear reactors and their causes. Nucl Saf 15:79, 466, 742
20. Floyd HL II (1986) Reducing human errors in industrial electric power system operation, part I: improving system reliability. IEEE Trans Ind Appl IA-22(3):420–424
21. Boring RL, Griffith CD, Joe JC (2007) The measure of human error: direct and indirect performance shaping factors. In: Proceedings of the IEEE conference on human factors and power plants, pp 170–176
22. Kolaczkowshi A, Forester J, Lois E, Cooper S (2005) Good practices for implementing human reliability analysis (HRA). Report No. NUREG-1792, United States Nuclear Regulatory Commission, Washington, D.C., Apr 2005
23. Swain AD, Guttman HE (1975) Human reliability analysis applied to nuclear power. In: Proceedings of the annual reliability and maintainability symposium, pp 116–119
24. Pontecorvo AB (1965) A method of predicting human reliability. In: Proceedings of the 4th annual reliability and maintainability conference, pp 337–342
25. Dhillon BS (1986) Human reliability: with human factors. Pergamon Press, New York
26. Dhillon BS (2009) Human reliability, error, and human factors in engineering maintenance: with reference to aviation and power generation. CRC Press, Boca Raton
27. Dhillon BS (1999) Design reliability: fundamentals and applications. CRC Press, Boca Raton
28. Kanji GK, Asher M (1996) 100 methods for total quality management. Safe Publications, London
29. Dhillon BS (2005) Reliability, quality, and safety for engineers. CRC Press, Boca Raton

Chapter 8
Human Factors in Control Systems

8.1 Introduction

Control systems play a pivotal role in power generation, and over the years, control systems and the role of their control room human operators have changed quite dramatically. The activity of human operator has evolved from manually carrying out the process, to control system supervision. In turn, the human operator requires an in-depth knowledge of the process being monitored, the ability to make effective decisions within demanding constraints, effective man–machine interfaces, etc.

Needless to say, after the Three Mile Island (TMI) nuclear power plant accident in 1979, the human factors in control systems in the area of power generation have become a very important issue. Because a Nuclear Regulatory Commission (NRC) study reported the findings such as virtually non-existent of human engineering at TMI, violation of number of human engineering principles in control panel designs, and information required by operators was often non-existent, poorly located, ambiguous, or difficult to read [1, 2].

This chapter presents various important aspects of human factors in control systems.

8.2 Control Room Design Deficiencies that can Lead to Human Error

There are many control room design-related deficiencies that can lead to human error. Some of these deficiencies are as follows [3]:

- Controls of subsystems widely separated from their associated alarm annunciators.
- Controls and displays placed well beyond anthropometric reach and vision envelopes.
- Poor use of shape coding and mirror-imaged control boards.

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_8,

- Lack of proper barriers for switches or control knobs considered critical.
- Poor location of some controls that can result in inadvertent activation.
- Chart recorders containing too many parameters.
- Inconsistency in colour coding within a control room.
- Reflection and glare from lighting on involved instruments.
- Poor labelling practice, including inconsistency in abbreviations.
- Wrong use of major, intermediate, and minor scale markings on involved meters.
- Adjacent meters with non-identical scales that must be compared by operators.
- Illegible recorder printouts and use of qualitative instead of quantitative indicators.
- Too complex annunciator systems along with complex procedures/equipment to knowledge, silence, test, and reset alarms.
- Meters that malfunction with the pointer reading in the normal band of the scale.

8.3 Advantages of Considering Human Factors in Digital Control Room Upgrades, an Approach to Incorporate Human Factors Considerations in Digital Control Room Upgrades, and Recommendations to Overcome Problems When Digital Control Room Upgrades are Undertaken Without Considering Human Factors into Design

There are many advantages of considering human factors in digital control room upgrades. These advantages may be grouped under the following four general categories [4]:

- **Category I: Improved equipment specification and procurement**. In this case, all essential human factors considerations can be specified right from the very beginning of the project.
- **Category II: Increased operator acceptance**. In this case, potential operators can provide critical input to human factors design and evaluation.
- **Category III: Decreased need for back fits or redesigns**. In this case, essential changes can be carried out at earlier, less costly, stages of the design process.
- **Category IV: Increased plant availability**. In this case, operator controllable trips and inefficiencies can be avoided, and downtime for system installation and testing is shorter.

The steps of an approach considered quite useful to incorporate human factors considerations in digital control room upgrades are shown in Fig. 8.1 [4]. Step 1 is concerned with surveying the existing control room and its environment to determine requirements for the new computer-based workstations. Step 2 is

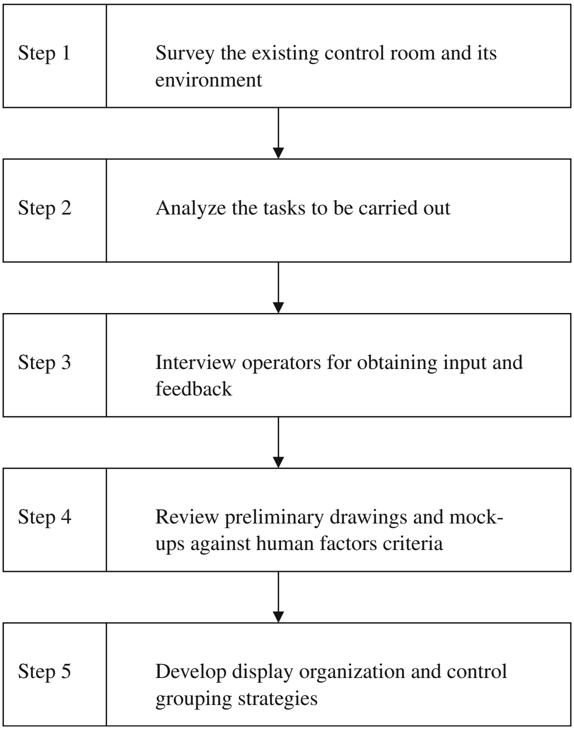


Fig. 8.1 Steps of an approach for incorporating human factors considerations in digital control room upgrades

concerned with analysing the tasks to be carried out; for developing information and control requirements.

Step 3 is concerned with interviewing operators for obtaining input and feedback to gather data from the end-users early in the design process. Step 4 is concerned with reviewing preliminary drawings and mock-ups against human factors criteria at early stage of design to avoid costly back fits.

Finally, Step 5 is concerned with developing display organization and control grouping strategies for applying to scenarios generated during the analysis to optimize design trade-offs.

The following recommendations classified under six areas are considered useful to overcome problems when digital control room upgrades are undertaken without considering human factors [4]:

- **Control devices**:
  1. Simplify confusing control operations.
  2. Position controls effectively/properly.
- **Displays**:
  1. Simplify all confusing displays.
  2. Ensure display configuration consistency.

3. Improve summary displays for providing better overall plant picture.
4. Include all types of required data on relevant displays.
5. Include graphics.
6. Add displays considered relevant.
7. Use colour effectively/properly.

- **Guidelines/Training**:

1. Provide appropriate guidelines for control and display design and development.
2. Provide appropriate guidelines for system implementation.
3. Provide appropriate hands-on training.
4. Ensure appropriate level of operator confidence through training.

- **System software**:

1. Ensure that system performs all required operations properly.
2. Ensure that system software collects all types of relevant data.
3. Optimize update rates and response time/capacity.
4. Minimize confusing and multiple steps necessary for obtaining data.

- **System hardware**:

1. Ensure that system hardware is appropriately designed for withstanding operational rigours.
2. Ensure that system contains all types of required hardware controls.
3. Ensure that equipment operation is not distracting or intrusive.

- **Facility**:

1. Ensure that system is configured so that the operator can easily and effectively carry out all required operations.
2. Ensure that surrounding environment clearly supports system operation and does not degrade it.
3. Ensure that all system parts are appropriately placed in the environment.

8.4 Common Problems Associated with Controls and Displays and Their Corrective Measures

There are many problems associated with controls and displays. The common ones and their corresponding corrective measures (in parentheses) are as follows [2]:

- Poor instrument grouping (make use of demarcation lines where necessary and rearrange during major retrofit).
- Displays/control too low or high (relocate as necessary within suitable anthropometric range).

- Poor labelling (use black letters on white black ground; consistent letter character size; and a hierarchical scheme).
- Glare and parallax on indicators (install appropriate diffusers in ceiling fixtures for distributing light more evenly and whenever possible choose instruments and less glass "distortion").
- Poor differentiation between various controls (make use of shape coding, colour code handles for all related systems, and shade background of all related controls).
- Inconsistent use of wording abbreviations (use same abbreviations consistently and use standard nomenclature and symbols for words).
- Controls near bottom edge of board inadvertently activated (install appropriate guard rail along edge of board in question).
- Poor engineering units or scaling on recorders/indicators (avoid suppressed scales, use units appropriate to parameter being measured, etc.)
- Nuisance alarms: annunciators (eliminate unnecessary alarms, revise set points on others (if possible), and perform alarm review).
- Controls: violation of stereotypes (keep directions of control handles in accordance with expectations of humans).

8.5 Human Engineering Discrepancies in Control Room Visual Displays

A study of a control room survey of several nuclear power plants reported a number of human engineering discrepancies in control room visual displays [5]. Six main areas of these discrepancies are shown in Fig. 8.2 [5].

Two discrepancies of the area "information displayed" were: (1) failed displays not apparent and (2) wrong display type. Three discrepancies of the area "scale markings" were: (1) poor numerical progression, (2) wrong scale graduation marks, and (3) log, multiple-scales. The following three discrepancies were associated with the area "display readability":

1. Informal meter scales
2. Characteristics and marking too small
3. Poor contrast (glare).

Two discrepancies of the area "usability of displays" were: (1) inappropriate scale or scale range limits and (2) conversion required. Three discrepancies of the area "scale zone markings" were: (1) no alarm points, (2) informal banding, and (3) no scale banding. Finally, the following two discrepancies were associated with the area "colour coding":

1. Poor colour usage
2. Inconsistent colour coding practices.

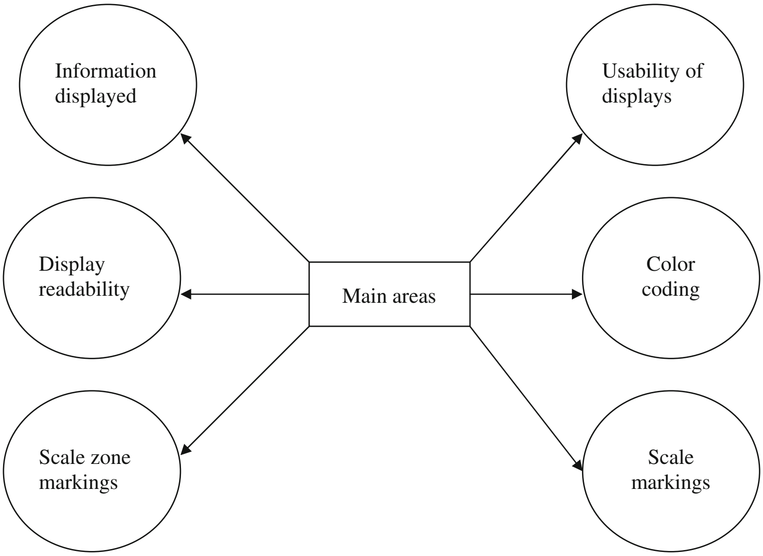


Fig. 8.2 Main areas of human engineering discrepancies in nuclear power plants' control room visual displays

8.6 Human Factors Guidelines for Digital Control System Displays

Over the years, a large number of human factors guidelines for digital control system displays have been developed [6–9]. These guidelines cover areas such as follows [9]:

- **Screen organization and layout**. The specific topics addressed in this area include screen size, display density, grouping of information, display partitioning, sequence of information, multiple-page displays, and inter-frame navigation.
- **Colour and other coding**. The specific topics addressed in this area include colour usage, colour assignments, icons and symbols, font, brightness, line sizes, geometric shapes, contrast reversal, blinking, combination of codes, and magnitude.
- **Windows**. The specific topics addressed in this area include alert boxes, general guidelines, dialogue boxes, and windows on real-time systems.
- **Screen structures and content**. The specific topics addressed in this area include labels, error messages, character size, cursor, user aids, abbreviations and acronyms, continuous text, data entry, and alphanumeric codes.
- **Alarms**. The specific topics addressed in this area include auditory alert, alarm system controls, alarm lists, general guidelines, reduction and prioritization, integration with other aids, and alarm message content.

- **Control-Display integration.** The specific topics addressed in this area include manual/auto stations, controls on mimics, permissive and tag outs, user dialogue, and system feedback.
- **Information formats**. The specific topics addressed in this area include general guidelines, band charts, graphs and labels, analogue representation, binary indication, linear profile, trend plot, data maps, range bar, single value line chart, and circular profile.
- **Input/control devices**. The specific topics addressed in this area include keyboard, touch screen, membrane keyboard, X–Y controller/mouse, track ball, and light pen.
- **Overall system requirements**. The specific topics addressed in this area include display of dynamic data and response time.
- **Large screen displays**. The specific topics addressed in this area include use and types and readability and visibility.
- **Menu design**. The specific topics addressed in this area include menu format, item selection, general guidelines, supplements to menus, and hierarchical menus.
- **Hardware**. The specific topics addressed in this area include glare, luminance, flicker and image polarity, and hard copy devices.

Human factors guidelines for certain above areas and specific topics are presented below [9].

8.6.1 Windows

Although windows provide flexibility and organization for the potential users, but require proper window management on the part of involved users or designers, the following two are the general styles of windows:

- **Tiled**. This type of windows may be placed to edge or within a specified area on a formatted display, but at all times, the contents of all windows are visible.
- **Overlapped**. With this type of windows, it is possible to arrange multiple windows like pieces of paper on a desk top, so that one may appear to a certain degree to overlap another. Overlapping windows provide a mechanism for a temporary display to be viewed as well as provide the place keeping or reference advantage of keeping a certain portion of an earlier display in an easy access and view.

Nonetheless, some of the useful guidelines in the area of windows are as follows [6, 9–12]:

- Provide an effective means to control the size of the window. More specifically, resizing should affect the viewing area only, not the window contents' format.
- Provide an effective means to close the window.

- Standardize effectively the format for windows.
- Provide a reserved screen area (i.e. a window tile) for display of pop-up control stations where soft control stations are not displayed on a continuous basis, as on schematic overview displays.
- Provide dedicated window areas (tiles) for the display of user-selected information when windows are desired on formatted real-time displays.
- Provide a clear path to choose information for each and every window (e.g. provide a menu of window options).
- Design the display in such a way that it is impossible to change out and then recall the parent display with the same windowed information as it had on it when deselected, in situation where windows for user-selected information are provided on formatted real-time displays.
- Ensure that for tiled windows, pre-format information that may be assigned to the window, so it properly fits within the tile.
- Ensure that pre-format information is available for display in tiled windows to fit the window so that there is no need for the user to devote time or attention to manipulating the window, other than simply choosing what is to be presented.
- Provide a proper means to restore the original display rapidly, in situations where windows will overwrite information on real-time displays (e.g. dialogue boxes, pull-down menus, or alert boxes).

8.6.2 Alarms

In the design of displays for digital control systems, alarm management is a major consideration. Over the years, many human factors-related guidelines in the area of alarms have been developed [6, 13–15]. Some of the guidelines to aid in determining the necessity of alarms are as follows [9]:

- Avoid activating alarms for equipment that is out of service for some type of maintenance. Furthermore, when equipment is taken out of service, its all associated alarms should be disabled until it (i.e. equipment) is put back into service.
- Ensure that the amount and content of alarm-related information to be displayed in real time is based on what the operator requires to respond to the alarm effectively.
- Ensure that the number of levels of alarms is kept to a minimum.
- Avoid activating alarms as part of a normal operating sequence, i.e. during plant/system start-up or any other planned evolution.
- Provide appropriate alarms for warning of conditions that could affect personnel safety or could result in equipment damage.

8.6.3 Manual/Auto Stations, Controls on Mimics, and Permissive and Tag Outs

Generally, in the published literature, the human factors considerations in design of "soft" (i.e. software rather than mechanical) control capabilities have not been given much attention. Nonetheless, some of the guidelines that could be useful in this area are as follows [9]:

- Label control stations unambiguously to highlight the controlled process or component.
- Ensure that different types of soft control stations are distinctively different in appearance.
- Ensure that the indicators shown on the control station are labelled according to their function or the quantities displayed.
- Ensure that the order of control stations within the framework of an array is based on logical relationships among the controls such as system relationships, criticality, or sequence of use.
- In the event, when an array of soft stations are presented, highlight the one selected for operation.
- Display the actual status of the controlled component/unit.
- Provide a proper means to indicate non-availability of control stations due to unsatisfied permissive or tag outs.

Additional information on guidelines concerned with the topic of this section is available in Ref. [9].

8.6.4 Inter-Frame Navigation

Some of the inter-frame-related guidelines are as follows [9, 16]:

- Ensure that a map of the display network is provided on request.
- Aim to provide all the necessary information required to respond to time-critical situations, on a single display page.
- Consider providing for random access to displays by means of command entry for sequential access systems or menu.
- Avoid requiring the user to wait for an intermediate step to be completely displayed prior to the user can proceed to the next step in the involved selection process.
- Ensure that the organization of the network of displays is according to some easily understood principle, such as frequency of use, sequence of use in start-up, or interconnections among plant systems.
- Make use of dedicated function keys for providing one-button access to time-critical controls and information.

- Ensure that information and controls to displays are assigned according to some acceptable meaningful logic.
- Provide an effective return-to-previous-page capability.
- Ensure that display pages are organized in such a way that the displays that are likely to be used in sequence can be easily accessed by a single action.
- Provide a type-ahead capability that allows the system to process and act on inputs while the intermediate displays are being drawn, in situations where menu or sequential access cannot be avoided.
- Provide an appropriate paging capability in conditions where displays can only be accessed indirectly (i.e. by means of a menu).

8.6.5 Colour Usage

Over the years, past experiences clearly indicate that colour aid performance in both search and identification-related tasks when the code is unique and known in advance [17, 18]. Two most useful guidelines in the area of colour usage are as follows [9]:

- Ensure that all colour codes are simple, consistent, and unambiguous.
- Ensure that the meaning assigned to particular colours are clearly consistent across all applications within the control room.

Additional guidelines on colour usage are available in Refs. [10, 11].

8.7 Human Performance-Related Advanced Control Room Technology Issues

Although advanced control room technology has the potential to improve system performance, there is also potential to negatively impact human performance and create precursors for the occurrence of human errors. Some of the human performance-related advanced control room technology issues are as follows [19, 20]:

- Shift from physical to highly cognitive inclined workload impairing the ability of operator to process and monitor all types of relevant data.
- Loss of vigilance of operator due to automated systems resulting in decrease in ability to detect off-normal conditions.
- Ill-defined and poorly organized tasks resulting from poor allocation of function-related strategies.
- Very high shifts in operator workload (i.e. workload transition) whenever a computer failure occurs.

- Difficulty in understanding how advanced systems work which can result in either a lack of complete acceptance of operator aids or too much reliance on them.
- Increment in the operator's cognitive workload related to the management of the interface (e.g. scaling, positioning, and opening windows).
- Considerable loss of skill proficiency for the occasional performance of functions that are generally automated.
- Problems in navigating through and finding pertinent information presented in a computer-based workspace.
- Loss of "situation awareness" of the operator which makes it rather difficult to assume direct control when necessary.
- Loss of ability for using well-learned, rapid eye-scanning patterns and pattern recognition from spatially fixed parameter displays, particularly in the case of highly flexible CRT-type interfaces.

Additional information on the above issues is available in Ref. [19].

8.8 Control Room Annunciator's Human Factors-Related Evaluation

In order to alert control room operators to plant conditions, a typical commercial nuclear power plant control room can have from 1,000 to 2,000 annunciators [21]. Since these annunciators are activated whenever plant parameter limits exceed, they are very important to system safety design. Thus, a study was conducted to highlight specific problem areas conducive to operator difficulty as well as to provide specific and generic solutions to those problems [21]. The study evaluated the annunciator systems in four nuclear reactor facilities and formally interviewed 39 reactor operators. Each operator interviewed 39 reactor operators. Each operator interviewed was asked a series of structured questions such as presented in Table 8.1 [21].

The classifications of the end results of the information collected and analysed are shown in Fig. 8.3 [21].

The items belonging to classification: lack of organization and consistency are as follows:

- Annunciators are rarely designed and placed in a logical, consistent, or rational manner.
- Annunciators are generally poorly organized and structured with respect to function, system impact, response immediacy, or importance.
- A lack of standardization in colour coding, labelling, design, script, acoustic alarm frequency, contrast, timbre, operating logic, and abbreviations.

Table 8.1 Questions asked to nuclear power plant control room operators

Question no.	Question
1	Are any of the annunciator displays difficult to comprehend or read?
2	How easy to use are the procedures associated with annunciators?
3	Are you happy with the existing locations of all the annunciators?
4	Have you ever had any past difficulties or specific areas of concern with any annunciator displays?
5	Is here a situation for which no annunciator available?
6	How helpful are the annunciators to diagnose plant conditions?
7	What type of annunciator-related hardware do you consider the best?
8	How cumbersome or easy is it to maintain the existing annunciators?
9	Do you have any suggestions for improving annunciator systems, training, and the approaches used by operators?
10	Which annunciators in your opinion are most useful?

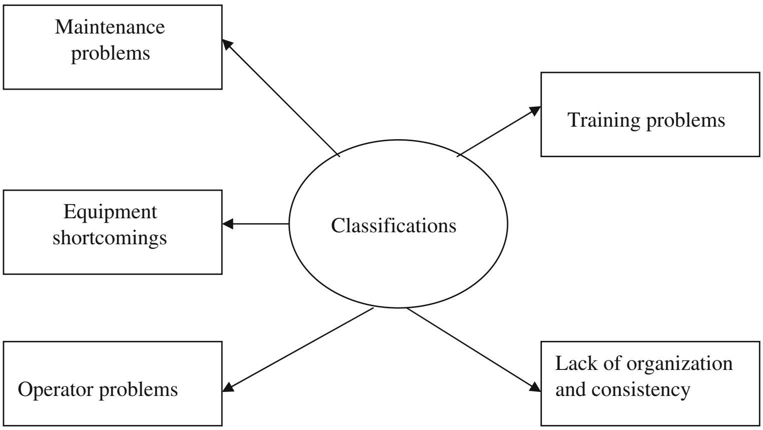


Fig. 8.3 Classifications of the end results of the control room annunciators' human factors-related information collected and analysed

The items belonging to classification: operator problems are as follows:

- Annunciators are frequently used for displaying various types of unimportant or relatively minor conditions.
- In the event when a major system failure occurs, many alarms that are only indirectly concerned with the primary failure are triggered. In turn, this significantly increases the information load that concerned operators must cognitively process to correctly highlight the primary failure source.
- For optimum viewing, letter sizes and labelling are unsatisfactory.

The items belonging to classification: equipment shortcomings are as follows:

- Some control room annunciators have quite low credibility with operators because of a rather high number of misleading or false alarms.
- Some annunciators are not possessed with a press-to-test device to test bulb and circuit.
- Some annunciators are not equipped with an alarm override switch such as set-point adjustment that can be utilized during maintenance for preventing constant and recurring acoustic alarms.
- Generally, very little descriptive information is provided on window faces for orienting potential operators towards proper corrective measures.
- Annunciators do not totally utilize existing computer display and logic capability for filtering or reducing the number of meaningless alarms, providing automatic default action if the operator overlooks to carry out necessary action, helping the operator to focus on the basic cause of a given alarm, and providing written or coded procedures for operators so that appropriate corrective actions can be undertaken.
- Generally, there is no systematic correspondence between annunciator display elements and the controls utilized for rectifying the alarms.

The items belonging to classification: training problems are as follows:

- Some guides-related documentation is inaccurate or incomplete.
- There is quite little agreement among operating personnel on what annunciators are essential or most important for plant operations.

Finally, the items belonging to classification: maintenance problems are as follows:

- Generally bulb and logic card-related repair is relatively quite frequent.
- In some alarm systems, operators are required to make their own tools to change bulbs.
- Tag-out procedures for annunciator maintenance are very poor in some plants.

The above control room annunciators' human factors-related evaluation results are considered very useful to improve human factors associated with control room annunciators.

8.9 Problems

1. List at least 12 control room design deficiencies that can lead to human error.
2. Discuss the advantages of considering human factors in digital control room upgrades.

3. Describe an approach to incorporate human factors considerations in digital control room upgrades.
4. Discuss the common problems associated with controls and displays and their corrective measures.
5. What are the main areas of human engineering discrepancies in nuclear power plants' control room visual displays?
6. Discuss human factors guidelines for digital control system displays.
7. List at least ten human performance-related advanced control room technology issues.
8. Write an essay on human factors in control systems.
9. Discuss recommendations to overcome problems when digital control room upgrades are undertaken without considering human factors into design.
10. Discuss human engineering discrepancies in the following three areas concerning nuclear power plants' control room visual displays:

    - Display readability.
    - Scale zone markings.
    - Colour coding.

References

1. Malone TB et al (1980) Human factors evaluation of control room design and operator performance at Three Mile Island-2, Final Report. Report No. NUREG/CR-1270, vol 1. Nuclear Regulatory Commission (NRC), Washington, DC
2. Tennant DV (1986) Human factors considerations in power plant control room design. In: Proceedings of the 29th power instrumentation symposium, pp 29–36
3. Brooks DM, Wilmington CR, Wilmington TG (2008) Role of human factors in system safety. In: Proceedings of the international congress on advances in nuclear power plants, pp 62–75
4. Gaddy CD, Fray RR, Divakaruni SM (1991) Human factors considerations in digital control room upgrades. In: Proceedings of the American power conference, pp 256–258
5. Lisboa J (1992) Human factors assessment of digital monitoring systems for nuclear power plants control room. IEEE Trans Nucl Sci 39(4):9224–9932
6. Guidelines for Control Room Design Reviews. Report No. NUREG-0700, U.S. Nuclear Regulatory Commission (NUREG), Washington, DC
7. BeareAN, Gaddy CD, Taylor JC et al (1991) Human factors guidelines for fossil power plant control rooms and remote control stations. Report No. RP 2710-20, Electric Power Research Institute (EPRI), Palo Alto, California
8. Daniels RW, Oliver JA (1984) Enhancing fossil power plant design and operation: human factors guidelines. Report No. CS-3745, vol 1–3. Electric Power Research Institute, Palo Alto, California
9. Beare AN, Gaddy CD, Gilmore WE, Taylor JC, Fray RR, Divakaruni SM (1992) Human factors guidelines for fossil power plant digital control system displays. In: Proceedings of the IEEE conference on human factors and power plants, pp 248–253
10. Gilmore WE, Gertman DI, Blackman HS (1989) User-computer interface in process control. Academic Press, Boston
11. MIL-HDBK-761A (1989) Human engineering guidelines for management information systems, Department of Defense, Washington, DC

12. Billingsley PA (1988) Taking panes: issues in the design of windowing systems. In: Helander M (ed) Handbook of human-computer interaction. North-Holland Publishing, Amsterdam, pp 200–209
13. Banks WE, Boone MP (1981) Nuclear control room annunciators: problems and recommendations. Report No. NUREG/CR-2147, Nuclear Regulatory Commission, Washington, DC
14. Rankin WL, Duvernoy KR, Ames KR, Morgenstern MH, Eckenrode RJ (1983) Near-term improvements for nuclear power plant control room annunciators. Report No. NUREG/CR-3217, Nuclear Regulatory Commission, Washington, DC
15. Seminara JL (1988) Control room deficiencies, remedial options, and human factors research needs. Report No. EPRI NP-5795, Electric Power Research Institute, Palo Alto, California
16. Paap KR, Roske-Hofstrand RJ (1988) Design of menus. In: Helander M (ed) Handbook of human-computer interaction. North-Holland Publishing, Amsterdam, pp 80–87
17. Blackman HS, Gilmore (1988) The analysis of visual coding variables on CRT-generated displays. Proc Soc Inf Display 29(2):10–14
18. Christ RE (1990) Review and analysis of color coding research for visual displays. In: Venturino M (ed) Selected readings in human factors. Human Factors Society, Santa Monica, pp 108–115
19. O'Hara JM, Hall RE (1992) Advanced control rooms and crew performance issues: implications for human reliability. IEEE Trans Nucl Sci 39(4):919–923
20. Rasmussen J, Duncan K, Leplat J (eds) (1987) New technology and human error. Wiley, New York
21. Banks WW, Blackman HS, Curtis JN (1984) A human factors evaluation of nuclear power plant control room annunciators. In: Proceedings of the annual control engineering conference, pp 323–326

Chapter 9
Human Factors in Power Plant Maintenance

9.1 Introduction

In power plant maintenance, human factors play an important role because by improving the maintainability design of power plant systems, equipment, and facilities in regard to human factors helps to increase plant safety, availability, and productivity. In comparison to the aerospace industrial sector, interest in human factors-related issues in the power industrial sector is relatively new. Its history may be traced back to the 1970s, when the WASH-1400 Reactor Safety Study criticized the deviation of the design of displays and controls and their arrangement in the United States commercial nuclear power plants from the human factors engineering set standards [1].

Consequently, a study concerning the review of human factors in nuclear power plant control rooms in the United States was sponsored by the Electric Power Research Institute [2]. This study identified various major and minor human factors' shortcomings that can lead to poor effectiveness of the man–machine interface [2–4]. Needless to say, over the years, the occurrence of many human factors' shortcomings-related events in the area of power generation has lead to an increased attention to human factors in power plant maintenance.

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

9.2 Power Plant Systems' Human Factors Engineering Maintenance-Related Shortcomings

There are many human factors engineering maintenance-related shortcomings or deficiencies in power plant systems. A survey-based study has classified, in descending order, such shortcomings under the following six categories [5]:

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_9,

- **Category I: Inadequate clearance or limited access to carry out maintenance activities**. It means that there is inadequate clearance to carry out inspection activities, no room for the correct tool, etc.
- **Category II: Equipment poorly designed to facilitate all involved maintenance activities in an effective manner**. It means that the required tasks are too detailed to carry out with gloves and mask on, it is not possible to open all involved cabinet doors all the way, design is too complex (i.e., too difficult to repair), etc.
- **Category III: Systems/equipment inherently unreliable**. It means that flatbed fitter is under-designed and needs maintenance constantly, the system drifts and is unstable, overly sensitive controllers, etc.
- **Category IV: Personnel-related safety hazard**. It means poorly designed equipment in high radiation areas, no safety rail where is, say a 35-foot drop, oil on the floor from the main feed pumps, hydrogen unloading facility is dangerous, etc.
- **Category V: Impaired mobility for both equipment and involved personnel**. It means one way access to hatch into containment, lack of work platforms with proper ladders, no cargo elevators where required, no elevator access to the turbine deck, etc.
- **Category VI: Miscellaneous**. It includes items such as poor air conditioning, lack of effective standardization, and high-temperature environment.

9.3 Desirable Human Factors Engineering Maintenance-Related Attributes of a Power Plant's Well-Designed Systems and Elements Relating to Human Performance that Can Contribute to a Successful Maintenance Programme

There are many desirable human factors engineering maintenance-related attributes of a power plant's well-designed systems. A survey-based study reported the following 11 attributes [5]:

- **Attribute I: Ease of servicing and inspection**. It means ease of oil changes, easy to spot problems, good access for preventive maintenance-related activities, etc.
- **Attribute II: Ease of removal, disassembly, and repair**. It means easy removal of circuit breakers, modular design of rod controls, modules on roll-out rails, etc.
- **Attribute III: Effective movement and lifting capability**. It means built-in hoist always in place, access for vehicles, easy removal through roof, etc.

- **Attribute IV: Effective accessibility**. It means good access to rod controls for repair activities, easy access to repair compressors, good accessibility around the diesels, etc.
- **Attribute V: Avoidance of contaminated areas**. It basically means, for example, equipment placed in easily accessible locations well-outside areas considered "hot".
- **Attribute VI: Ease of system troubleshooting testing and monitoring**. It means control cabinet for boiler control easy to troubleshoot, engineered guards easy to test, built-in calibration system, good test jacks, and easy to input signals, etc.
- **Attribute VII: Availability of all required tools**. It means availability of all types of tools required, for example, all types of special tools provided for a complex assembly.
- **Attribute VIII: Highly reliable equipment**. It means reliable relays, highly reliable engineered safeguards actuation system, air compressor easy to operate, and rarely breaks down, etc.
- **Attribute IX: Good lay down area**. It basically means, for example, very good lay down area for turbine generator.
- **Attribute X: Good quality manuals and prints**. It means detailed operating instructions, readable prints, understandable procedures, etc.
- **Attribute XI: Miscellaneous**. It includes items such as frequent use of mock-ups for training and fail-safe design.

Additional information on the above attributes is available in Ref. [5].

There are many elements relating to human performance that can contribute to a successful maintenance programme in a power plant. Six of these elements are shown in Fig. 9.1 [6].

Additional information related to elements shown in Fig. 9.1 is available in Ref. [6].

9.4 Performance Goals of a Power Plant that Drive Decisions About Human Factors and a Study of Human Factors in Power Plants

Past experiences clearly indicate that there are many performance goals of a power plant that drive, directly or indirectly, maintenance-related decisions about human factors. These goals may be categorized under the following three classifications [7]:

- **Classification I**: Plant productivity
- **Classification II**: Plant availability
- **Classification III**: Plant safety.

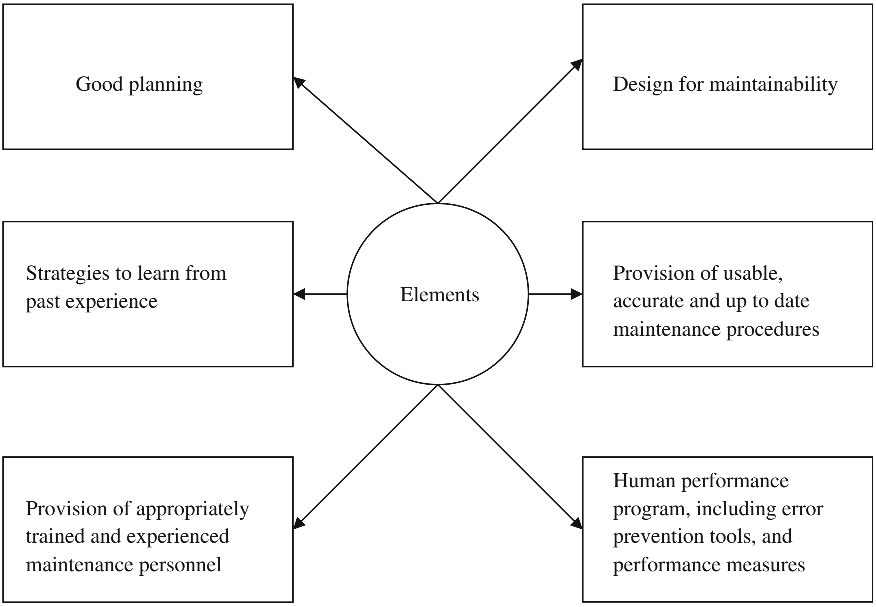


Fig. 9.1 Elements relating to human performance that can contribute to a successful maintenance programme in a power plant

Classification I goals include items such as improving efficiency, reliability, and motivation of all involved personnel. Classification II goals include increasing the time period, the power plant can operate at its full power generation capacity by reducing human errors that, directly or indirectly, contribute to equipment failures or increase equipment corrective maintenance time. Finally, Classification III goals include minimizing injury to all involved personnel, damage to equipment/ system, and in the case of nuclear power plants, reducing the radiation exposure to humans and eliminating altogether the potential for release of radioactivity to the environment.

A study of maintenance in nine power generation plants (i.e., five nuclear and four fossil fuel) in regard to human factors reported various types of, directly or indirectly, human factors-related problems. This study was quite wide ranging in scope, extending to an examination of items that included designs, environmental factors, tools, procedures, facilities, spares, and organizational factors.

The findings of this study were grouped under 16 classifications shown in Fig. 9.2 [3, 5]. Some of the classifications shown in the figure are described below.

Classification I: environmental factors is concerned with human factors' problems pertaining to environment and two examples of such problems are a high variability of illumination and heat stress. An example of the problems belonging to Classification II: communications is an inadequate capacity of the existing

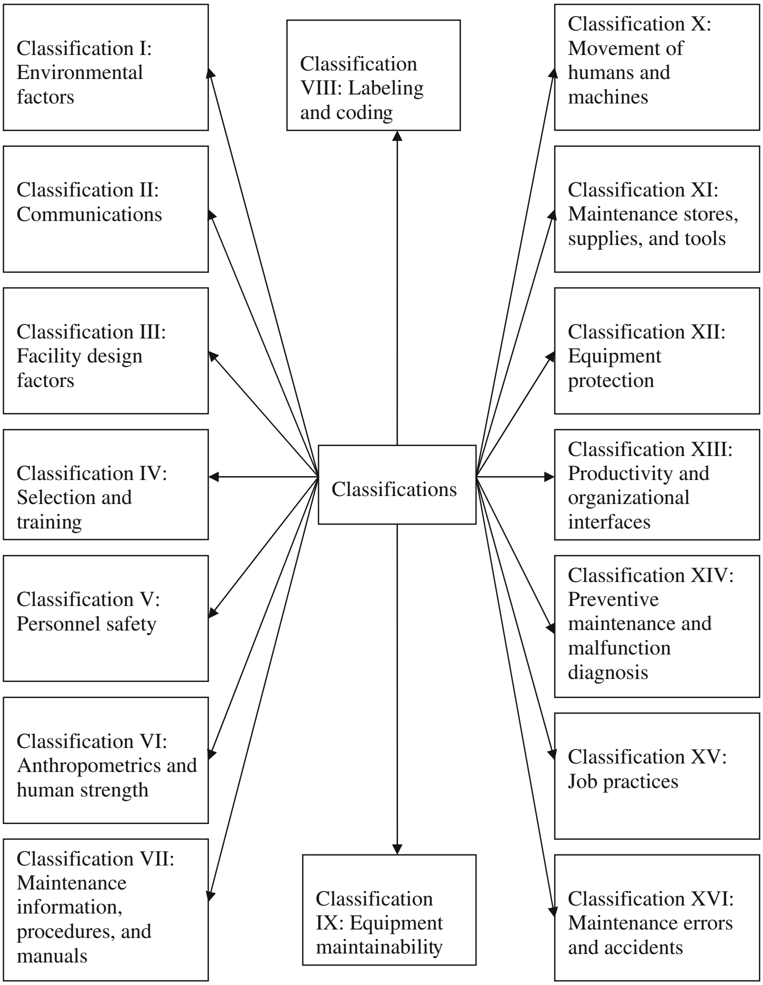


Fig. 9.2 Classifications of the findings of a study of human factors in power plants

communications system to meet the volume of communications' traffic needed throughout the plant, particularly during outages.

Classification III: facility design factors is concerned with, directly or indirectly, human factors' problems pertaining to facility design and three examples of such problems are poor temperature–ventilation control, high noise level, and inadequate facility to store contaminated equipment. An example of the problems belonging to Classification IV: selection and training is the informality of the training process, with no properly defined selection criteria, and lacking validated screening methods or tools.

Classification V: personnel safety is concerned with problems such as radiation exposure, heat prostration, steam burns, and chemical burns. An example of the problems belonging to Classification VI: anthropometrics and human strength is the lack of proper access to system/equipment requiring maintenance. Classification VII: maintenance information, procedures, and manuals are concerned with human factors-related problems such as inadequate manuals and poorly written procedures.

Three examples of the problems belonging to Classification VIII: labelling and coding are unsystematic replacement of labels lost or obscured over time, high likelihood of the occurrence of maintenance errors in multi-unit plants in which units are identical or very similar in appearance, and poorly descriptive label tags. An example of a problem belonging to Classification IX: equipment maintainability is the placement of units/parts/components of equipment in locations that are difficult to access from a normal work position.

Information on the remaining classifications is available in Refs. [3, 5].

9.5 Advantages of Human Factors Engineering Applications in Power Plants

Various studies conducted over the years have clearly indicated that there are many advantages of human factors engineering applications in the area of power plant maintenance [3, 4]. Nonetheless, the advantages of the application of human factors engineering in the area of power generation in general that directly or indirectly concern maintenance may be grouped under two main categories as shown in Fig. 9.3 [7–10].

Category I: reductions includes the following reduction-related advantages:

- Reduction in needless costs.
- Reduction in the occurrence of human error.
- Reduction in number and qualifications of personnel required.
- Reduction in consequences of human error (i.e., number and severity of injuries and damage to equipment).
- Reduction in job dissatisfaction of personnel (i.e., absenteeism and turnover).
- Reduction in training requirements and attrition.
- Reduction in wasted time and motion.

Category II: increments includes the following increment-related advantages:

- Increases in safety, productivity, and availability.
- Increases in reliability and efficiency of personnel performance.
- Increases in adequacy of communications.
- Increases in job satisfaction of personnel (i.e., motivation, confidence, and commitment to achieving plant goals).
- Increases in cost-effectiveness of training.

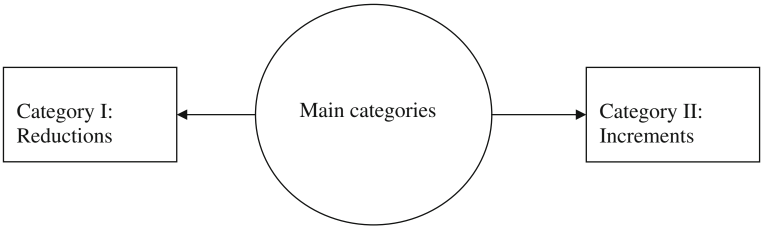


Fig. 9.3 Main categories of advantages of the application of human factors engineering in power generation

9.6 Human Factors' Methods to Assess and Improve Power Plant Maintainability

There are many human factors methods that can be used for assessing and improving power plant maintainability. Five of these methods are as follows [3, 4, 11]:

- Critical incident method
- Task analysis
- Structured interviews
- Maintainability checklist
- Potential accident/damage analyses.

All of the above methods are described below, separately.

9.6.1 Critical Incident Method

Various studies conducted, over the years, clearly indicate that the history of maintenance errors, near-mishaps, or accidents can provide very useful information concerning needed maintainability-related improvements. The critical incident method is a very useful tool for examining such case histories with respect to human factors. The application of this method calls for making appropriate arrangements to meet individually with appropriate personnel of maintenance organization under consideration. During the meeting, each of these individuals is asked the following three questions:

- **Question No. 1**: Give one example of a plant system or unit of equipment that "in your opinion" is well "human-engineered" or simple and straightforward to maintain, and describe the system/unit by emphasizing the appropriate features that clearly makes it good from the perspective of maintainers.
- **Question No. 2**: Give one example of a maintenance accident, near mishap, or error with serious or potentially serious consequences, based on your personal experience over the time period. Furthermore, describe all the specifics of the case involved and indicate all the possible ways the situation could have been averted.

- **Question No. 3**: Give one example of a plant system or unit of equipment that "in your opinion is not properly human-engineered" or is poorly designed from the perspective of maintenance personnel and that has caused or could cause a safety hazard, a human error, or damage to equipment.

After analysing the collected data, necessary changes required for improvements are recommended.

9.6.2 Task Analysis

This method is used to assess the needs of equipment maintainers for effectively working with hardware to perform a specified task. The analyst, in addition to making careful observations concerning impediments to effective maintainability, records and oversees each task element and completion and start times. The observations are grouped under the following 16 classification [3, 4]:

- Maintenance crew interactions
- Training needs
- Equipment maintainability design features
- Facility design features
- Decision-making factors
- Availability of necessary maintenance-related information (e.g., manuals, procedures, and schematics)
- Lifting or movement aids
- Workshop adequacy
- Environmental factors
- Access factors
- Tools and job aids
- Supervisor–subordinate relationships
- Communication
- Equipment damage potential
- Spare-parts retrieval
- Personnel hazards.

Additional information on this approach is available in Ref. [11].

9.6.3 Structured Interviews

This is one of the most efficient methods used for collecting maintainability data in the shortest possible time period. The method is based on the assumption that repair persons and their supervisors and others close to equipment/system maintainability problems, normally provide most useful information regarding difficulties involved in performing their tasks the best possible way.

A fixed set of questions such as presented below are asked during a structured interview [3, 11].

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

After analysing the data collected by asking questions such as above, necessary recommendations for improvements are made. Additional information on structured interviews is available in Ref. [11].

9.6.4 Maintainability Checklist

This is a quite useful method and is based basically on the survey study reported in Ref. [5]. The checklist is divided into the following 14 distinct topical areas [4, 5]:

- Equipment/system maintainability
- Equipment/system protection
- Personnel safety
- Maintenance information
- Anthropometrics and human strength
- Facilities
- Preventive maintenance
- Tools, spares, and stores
- Environmental factors
- Coding and labelling
- Communications
- Selection and training
- Job and organizational factors
- Radiation protection.

After analysing the information collected in the above 14 areas, appropriate decisions are made. Additional information on maintainability checklist is available in Ref. [11].

9.6.5 Potential Accident/Damage Analyses

This is a structured method often used for assessing the accident, damage, or potential error inherent in a given task. The starting point for determining the potential for the occurrence of mishaps in the performance of a given maintenance task is to establish a procedure that describes effectively the task under consideration. Subsequently, the interviewer of the interviewee (e.g., repair person) asks the following question for each task element [3, 11]:

Is there high, medium, or low chances for the occurrences of an error/an accident/damage to system/equipment/unit in carrying out, say, Step X?

After analysing all the collected data, recommendations for changes to items such as system/equipment/unit, procedures, and facility are made. Additional information on potential accident/damage analyses is available in Ref. [11].

9.7 Problems

1. Discuss power plant systems' human factors engineering maintenance-related shortcomings.
2. What are the desirable human factors engineering maintenance-related attributes of a power plant's well-designed systems?
3. Discuss at least six elements relating to human performance that can contribute to a successful maintenance programme.
4. Discuss the three classifications of performance goals of a power plant that drive directly or indirectly, maintenance-related decisions about human factors.
5. What are the advantages of human factors engineering applications in power plants?
6. Describe at least three human factors methods that can be used to assess and improve power plant maintainability.
7. Compare critical incident method with task analysis.
8. Write an essay on human factors in power plant maintenance.
9. Discuss the classifications of the findings of the study of human factors in power plants.
10. Write down at least five questions that can be asked during a structured interview.

References

1. US Nuclear Regulatory Commission (1975) Reactor safety study: an assessment of accident risks in US commercial nuclear power plants. Report No. WASH-1400, US Nuclear Regulatory Commission, Washington

2. Seminara JL, Gonzalez WR, Parsons SO (1976) Human factors review of nuclear power plant control room design. Report No. EPRI NP-309, Electric Power Research Institute (EPRI), Palo Alto
3. Seminara JL, Parsons SO (1985) Human factors engineering and power plant maintenance. Maintenance Manage Int 6:33–71
4. Dhillon BS (2009) Human reliability, error, and human factors in engineering maintenance: with reference to aviation and power generation. CRC Press, Boca Raton
5. Seminara JL, Parsons SO (1981) Human factors review of power plant maintainability. Report No. EPRI NP-1567, Electric Power Research Institute, Palo Alto
6. Penington J, Shakeri S (2006) A human factors approach to effective maintenance. In: Proceedings of 27th annual Canadian Nuclear Society (CNS) conference, pp 1–11
7. Kinkade RG (1988) Human factors primer for nuclear utility managers. Report No. EPRI NP-5714, Electric Power Research Institute, Palo Alto
8. Shriver EL, Zach SE, Foley JP (1982) Test of job performance aids for power plants. Report No. EPRI NP. 2676, Electric Power Research Institute, Palo Alto
9. Pariftt B (1986) First use: frozen water garment use at TMI-2. Report No. EPRI 4102B (RP 1705), Electric Power Research Institute, Palo Alto
10. Annual Report (1982) Electric Power Research Institute, Palo Alto
11. Seminara JL (1982) Human factors methods for assessing and enhancing power plant maintainability. Report No. EPRI NP-2360, Electric Power Research Institute, Palo Alto

Chapter 10
Human Error in Power Plant Maintenance

10.1 Introduction

In power plants, maintenance is an important activity and it consumes a significant proportion of the total amount of money spent on power generation. A number of studies conducted over the years indicate that human error in maintenance is an important factor in the occurrence of power generation safety-related incidents [1, 2]. For example, a study of nuclear power plant operating experiences reported that due to errors in the maintenance of some motors in the rod drives, many motors ran in a backward direction and withdrew rods altogether, rather than inserting them [3].

Maintenance error cost in power plant maintenance, including opportunity costs and restoration costs, is potentially very high, the damage impact on the involved equipment/system may decrease its life significantly, and very serious potential hazards to humans may occur. Therefore, because of potentially very serious consequences such as these to human safety and equipment/system function, the prevention of the occurrence of human errors in maintenance-related tasks is receiving increasing attention in power generation.

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

10.2 Facts, Figures, and Examples

Some of the facts, figures, and examples directly or indirectly concerned with human error in power plant maintenance are presented below.

- As per Refs. [4, 5], a number of studies reported that between 55 and 65 %, human-performance-related problems surveyed in the area of power generation were concerned with maintenance activities.
- As per Ref. [6], 25 % of unexpected shutdowns in Korean nuclear power plants were due to human errors, out of which more than 80 % of human errors were resulted from usual testing and maintenance tasks.

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_10,

- As per Ref. [9], during the period from 1965 to 1995, a total of 199 human errors occurred in Japanese nuclear power plants, out of which 50 of them were concerned with maintenance tasks.
- As per Ref. [8], in the state of Florida, on Christmas Day in 1989, two nuclear reactors were shut down due to maintenance error and caused rolling blackouts.
- As per Ref. [9], maintenance errors account for around 60 % of the annual power loss due to human errors in fossil power plants.
- In 1990, in the area of nuclear power generation, a study of 126 human-error-related significant events revealed that about 42 % of the problems were linked to modification and maintenance [4].
- In the late 1990s, a blast at the Ford Rouge power plant in Dearborn, Michigan, due to a maintenance error killed six workers and injured many others [10, 11].
- A study of over 4,400 maintenance-related history records concerning a boiling water reactor (BWR) nuclear power plant covering the period from 1992 to 1994 revealed that about 7.5 % of all failure records could be attributed to human errors related to maintenance activities [12, 13].

10.3 Maintenance Tasks Most Susceptible to Human Error in Power Generation and Types of Human Errors in Digital Plant Protection Systems Maintenance Tasks

Over the years, various studies have been performed to identify maintenance tasks most susceptible to human error in power generation. As the result of these studies, the following five maintenance tasks in the area of nuclear power generation are found most susceptible to human error [14]:

- Replace reactor coolant pump (RCP) seals.
- Overhaul motor-operated valve (MOV) actuator.
- Test reactor protection system (RPS).
- Overhaul main feed water pump (MFWP).
- Overhaul mainstream isolation valves (MSIV).

In order to take advantage of digital technology, nowadays analogue RPSs are being replaced by the DPPS. The scope of the occurrence of human error incidence in DPPS during the performance of a maintenance task is very high, ranging from missing an important step of work procedure to intentional deviation of work procedure from the proper work procedure, in order to accomplish the task easily in uncomfortable environment or save time.

As the result of DPPS maintenance task analysis and published literature survey, the types of human errors in DPPS maintenance tasks are shown in Fig. 10.1 [15, 16].

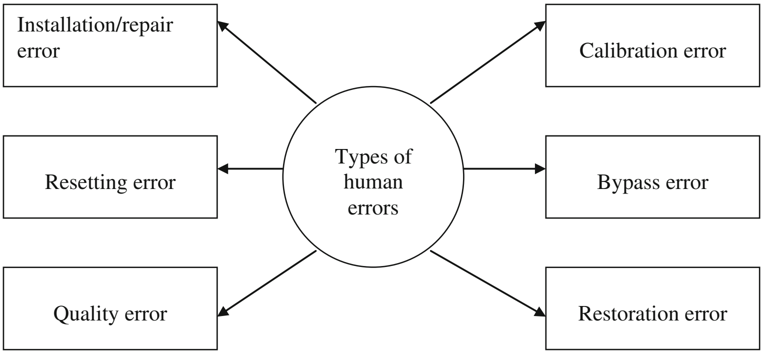


Fig. 10.1 Types of human errors in digital plant protection systems (*DPPS*) maintenance tasks

These errors are calibration error, quality error, installation/repair error, resetting error, restoration error, and bypass error. "Calibration error" is associated with an incorrect setting of trip limits or references. "Quality error" occurs basically due to carelessness and limited space for work or transport. Two examples of this type of error are too little or too much tightening of screws and deficient soldering/welding joints or insulation. "Installation/repair error" occurs when faulty parts are repaired or replaced during the refuelling maintenance process as a corrective or preventive measure.

"Resetting error" and "restoration error" occur from a failure to reset bistable process parameters after completion of a test and from an oversight to restore the system after completion of maintenance or a test, respectively. Finally, "bypass error" results whenever a channel is bypassed to carry out tests in that very channel.

10.4 Causal Factors for Critical Incidents and Reported Events Related to Maintenance Error in Power Plants and Classifications of Causes of Human Error in Power Plant Maintenance

There are many causal factors for critical incidents and reported events related to maintenance error in power plants. A study has identified ten causal factors presented in Table 10.1, in order of lowest to highest frequency of occurrence, for critical incidents and reported events concerned with maintenance error in power plants [17, 18].

"Oversights by maintenance personnel" and "adverse environment factors" are the seventh (or the least) most frequently occurring causal factors. "Oversights by maintenance personnel" are a small fraction of those errors that would be quite difficult to anticipate and "design out" of power plants. The "adverse environmental factors" include items such as the requirement for wearing protective

Table 10.1 Causal factors, in order of lowest to highest frequency of occurrence, for critical incidents and reported events concerned with maintenance error in power plants

Causal factor no.	Causal factor frequency of occurrence	Causal factor
1	Lowest	• Oversights by maintenance personnel
2	↓	• Adverse environmental factors
3		• Poor work practices
4		• Problems in facility design
5		• Poor unit and equipment identification
6		• Poor training
7		• Problems in moving equipment or people
8		• Deficiencies in equipment design
9		• Problems in tagging and clearing equipment for maintenance
10	Highest	• Faulty procedures

devices and garments in threatening environments that, in turn, restrict movement capabilities and visual field of a person, and the encouragement of haste by the need for minimizing stay time in, say, radioactive environments.

"Poor work practices" are the sixth most frequently occurring causal factor. Two examples of poor work practices are not taking the time required to erect a scaffold properly so that an item in mid-air can be accessed safely and not waiting for operators to accomplish the tagging and switching tasks necessary for disabling the systems requiring attention. "Problems in facility design", "poor unit and equipment identification", and "poor training" are the fifth most frequently occurring causal factors. "Problems in facility design" can contribute to accidents, and some examples of these problems are as follows:

- Insufficient clearances for repair workers.
- Inadequate equipment or transportation aids in the performance of maintenance tasks.
- Inadequately sized facilities causing an overly dense packaging of equipment systems and preventing proper performance of inspection or repair tasks.

"Poor unit and equipment identification" is the cause of an unexpectedly rather high number of accidents, and frequently, the problem is between identical items and time-to-time incorrect identification of potential hazards. "Poor training" is basically concerned with repair workers' unfamiliarity with the task or their lack of full awareness of the system characteristics and inherent dangers associated with the task under consideration.

"Problems in moving equipment or people" are the fourth most frequently occurring causal factor. These problems usually stem from the inability to use proper vehicular aids in shifting heavy units of equipment or from poor lifting capability. "Deficiencies in equipment design" are the third most frequently occurring causal factor for near-accidents/accidents revolved about equipment-design-associated problems. The factor includes items such as follows:

- The equipment not designed with proper mechanical safeguards to prevent the substitution of incorrect part for the correct replacement part.
- Poorly designed and inherently unreliable parts.
- Parts placed in inaccessible locations.
- Equipment installed incorrectly from the outset.

"Problems in tagging and clearing equipment for maintenance" are the second most frequently occurring causal factor in reported cases where potentially serious accidents/serious accidents could be attributed to an error/failure, directly or indirectly, concerned with the equipment clearance activities. "Faulty procedures" are the most frequently (highest/greatest) occurring causal factor in the mishaps reported. It incorporates items such as lack of adherence to a give procedure, wrong procedures, lack of specificity, and incompleteness. The following is a good example of faulty procedures:

> Due to poor judgement and not properly following prescribed guidelines, a ground was left on a circuit breaker. When the equipment/system was put back into service, the circuit breaker blew up and resulted in extensive property damage.

In this situation, the correct procedure would have called for clearing the ground before turning on the circuit breaker to its specified service.

Past experiences over the years indicate that there are many causes of human error in power plant maintenance. On the basis of characteristics obtained from modelling the maintenance task, causes for the occurrence of human errors in power plant maintenance may be categorized under the following four classifications [2]:

- **Classification I: design shortcomings in hardware and software**. These shortcomings include items such as deficiencies in the design of controls and displays, incorrect or confusing procedures, and insufficient communication equipment.
- **Classification II: disturbances of the external environment**. Some examples of these disturbances are the physical conditions such as temperature, ventilation, humidity, and ambient illumination.
- **Classification III: induced circumstances**. Some examples of these circumstances are momentary distractions, emergency conditions, and improper communications, which may result in failures.
- **Classification IV: human ability limitations**. A good example of these limitations is the limited capacity of short-term memory in the internal control mechanism.

10.5 Steps for Improving Maintenance-Related Procedures in Power Plants

Past experiences over the years clearly indicate that improving maintenance-related procedures in the area of power generation can be very useful, to reduce the occurrence of performance errors along with a corresponding increase in unit reliability. The upgrade of a maintenance procedure, generally, can be accomplished by following the eight steps shown in Fig. 10.2 [19].

It is to be noted that an improved or upgraded maintenance procedure can substantially contribute, directly or indirectly, to many diverse areas including fewer human-performance-related errors, higher level of employee morale, identification of necessary plant modifications, better unit reliability, and identification of required training. Additional information on this topic is available in Ref. [19].

10.6 Useful Guidelines to Reduce and Prevent Human Errors in Power Plant Maintenance

Over the years, professionals working in the area of power generation have proposed various guidelines to reduce and prevent human errors in power plant maintenance. Four of these guidelines considered most useful are shown in Fig. 10.3 [2].

The guideline "perform administrative policies more thoroughly" basically means motivating personnel involved in maintenance properly to comply with prescribed quality control procedures. The guideline "revise training programs for all involved maintenance personnel" basically means that training programs for personnel involved in maintenance should be revised as per the characteristic and frequency of occurrence of each extrinsic cause. The guideline "develop proper work safety checklists for maintenance personnel" basically means that maintenance personnel should be provided with appropriate work safety checklists, which can be effectively used to determine the possibility of occurrence of human error as well as the factors that may affect their actions before or subsequent to the performance of maintenance tasks.

Finally, the guideline "ameliorate design shortcomings" calls for overcoming shortcomings in areas such as plant layout, work environment, labelling, and coding, as shortcomings in design can reduce attention to the tasks and may even induce human errors. Additional information on the guidelines shown in Fig. 10.3 is available in Ref. [2].

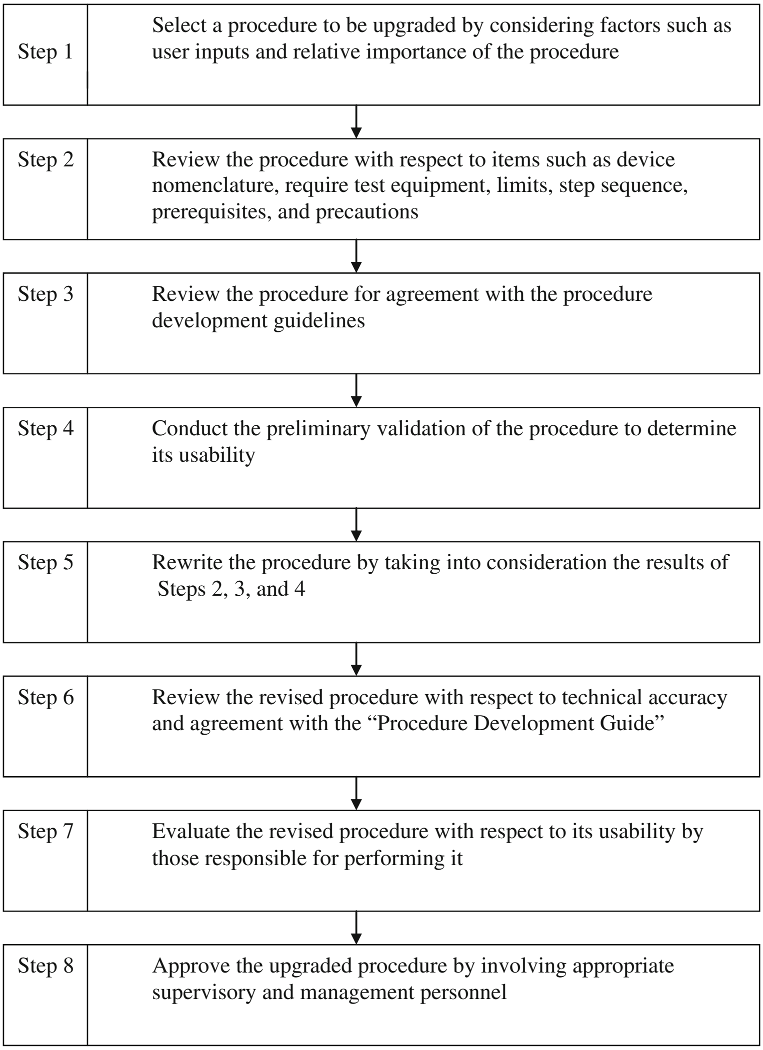


Fig. 10.2 Steps for upgrading a maintenance procedure

10.7 Methods for Performing Human Error Analysis in Power Plant Maintenance

There are many methods or models that can be used to perform human error analysis in power plant maintenance. Three of these methods/models are described below.

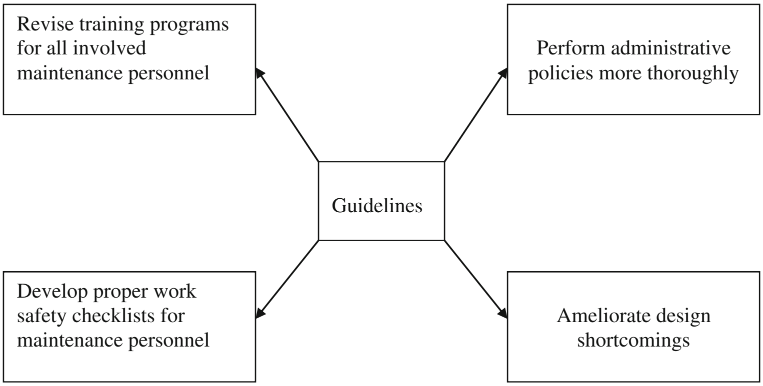


Fig. 10.3 Useful guidelines to reduce and prevent human errors in power plant maintenance

10.7.1 Maintenance Personnel Performance Simulation (MAPPS) Model

This model was developed by the Oak Ridge National Laboratory to provide estimates of performance measures of nuclear power plant maintenance manpower, and its development was sponsored by the United States Nuclear Regulatory Commission (NRC) [20]. The main objective for its development was the pressing need for and lack of a human reliability data bank pertaining to nuclear power plant maintenance-related tasks, for application in conducting probabilistic risk-assessment-related studies.

Some of the performance measures estimated by the MAPPS model are as follows:

- Probability of successfully accomplishing the task of interest.
- Probability of an undetected error.
- Identification of the most and least likely error-prone sub elements.
- Maintenance team stress profiles during task execution.

Finally, it is added that MAPPS model is an excellent tool to estimate important maintenance-related parameters and its flexibility allows it to be used in a wide variety of studies dealing with nuclear power plant maintenance activity.

Additional information concerning this model (i.e. MAPPS model) is available in Ref. [20].

10.7.2 Markov Method

This method is often used to perform probability analysis of repairable engineering systems, and it can also be used to perform human error analysis in the area of

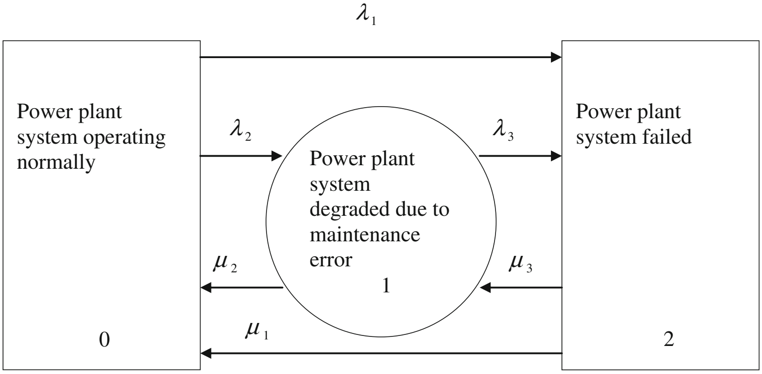


Fig. 10.4 Power plant system state space diagram

power plant maintenance. The method is described in detail in Chap. 4. Its application to perform human error analysis in the area of power plant maintenance is demonstrated through the following mathematical model:

Model

This mathematical model represents a power plant system that can only fail due to non-maintenance-related failures, but the occurrence of maintenance error degrades its performance. The power plant system state space diagram is shown in Fig. 10.4. Numerals in boxes and circle denote power plant system states.

The following assumptions are associated with the model:

- Maintenance error causes power plant system degradation, but not failure.
- The completely or partially failed power plant system is repaired.
- The power plant system can fail from its degraded state due to failures other than maintenance errors.
- The power plant system maintenance error and non-maintenance error failure rates are constant.
- All power plant system repair rates are constant, and the repaired system is as good as new.

The following symbols are associated with the model:

j is the power plant system state j; for $j = 0$ (power plant system operating normally), $j = 1$ (power plant system degraded due to maintenance error), and $i = 2$ (power plant system failed)

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

λ_1 is the power plant system constant failure rate

λ_2 is the power plant system constant maintenance error rate

λ_3 is the power plant system constant failure rate when in degraded state

μ_1 is the power plant system constant repair rate from fully failed state (i.e. state 2)

μ_2 is the power plant system constant repair rate from degraded state (i.e. state 1)
μ_3 is the power plant system constant repair rate from fully failed state (i.e. state 2) to degraded state (i.e. state 1).

By using the Markov method described in Chap. 4, we write down the following equations for Fig. 10.4 state space diagram:

$$\frac{dP_0(t)}{dt} + (\lambda_1 + \lambda_2)P_0(t) = \mu_2 P_1(t) + \mu_1 P_2(t) \tag{10.1}$$

$$\frac{dP_1(t)}{dt} + (\mu_2 + \lambda_3)P_1(t) = \mu_3 P_2(t) + \lambda_2 P_0(t) \tag{10.2}$$

$$\frac{dP_2(t)}{dt} + (\mu_1 + \mu_3)P_2(t) = \lambda_1 P_0(t) + \lambda_3 P_1(t) \tag{10.3}$$

At time $t = 0$, $P_0(0) = 1$, $P_1(0) = 0$, and $P_2(0) = 0$.
By solving Eqs. (10.1–10.3), we get

$$\begin{aligned} P_0(t) = {} & \frac{\mu_2\mu_1 + \lambda_3\mu_1 + \mu_2\mu_3}{X_1X_2} \\ & + \left[\frac{\mu_2X_1 + \mu_1X_1 + \mu_3X_1 + X_1\lambda_3 + X^2 + \mu_2\mu_1 + \lambda_3\mu_1 + \mu_2\mu_3}{X_1(X_1 - X_2)}\right]e^{X_1t} \\ & + \left\{1 - \frac{(\mu_2\mu_1 + \lambda_3\mu_1 + \mu_2\mu_3)}{X_1X_2}\right. \\ & \left. - \left[\frac{\mu_2X_1 + \mu_1X_1 + \mu_3X_1 + X_1\lambda_3 + X_1^2 + \mu_2\mu_1 + \lambda_3\mu_1 + \mu_2\mu_3}{X_1(X_1 - X_2)}\right]\right\}e^{X_2t} \end{aligned} \tag{10.4}$$

where

$$X_1, X_2 = \left[-A \pm \left\{A^2 - 4\left(\mu_2\mu_1 + \lambda_3\mu_1 + \mu_2\mu_3 + \mu_1\lambda_2 + \lambda_2\mu_3 + \lambda_2\lambda_3 + \mu_2\lambda_1 + \lambda_1\mu_3 + \lambda_1\lambda_3\right)\right\}^{1/2}\right]/2$$
$$A = \lambda_2 + \lambda_1 + \lambda_3 + \mu_2 + \mu_1 + \mu_3$$
$$X_1X_2 = \mu_2\mu_1 + \lambda_3\mu_1 + \mu_2\mu_3 + \mu_1\lambda_2 + \lambda_2\mu_3 + \lambda_2\lambda_3 + \mu_2\lambda_1 + \lambda_1\mu_3 + \lambda_1\lambda_3$$

$$\begin{aligned} P_1(t) = {} & \frac{\lambda_2\mu_1 + \lambda_2\mu_3 + \lambda_1\mu_3}{X_1X_2} + \left[\frac{X_1\lambda_2 + \lambda_2\mu_1 + \lambda_2\mu_3 + \lambda_1\mu_3}{X_1(X_1 - X_2)}\right]e^{X_1t} \\ & - \left[\frac{\lambda_2\mu_1 + \lambda_2\mu_3 + \lambda_1\mu_3}{X_1X_2} + \frac{X_1\lambda_2 + \lambda_2\mu_1 + \lambda_2\mu_3 + \lambda_1\mu_3}{X_1(X_1 - X_2)}\right]e^{X_2t} \end{aligned} \tag{10.5}$$

$$\begin{aligned} P_2(t) = {} & \frac{\lambda_2\lambda_3 + \mu_2\lambda_1 + \lambda_1\lambda_3}{X_1X_2} + \left[\frac{X_2\lambda_1 + \lambda_2\lambda_3 + \lambda_1\mu_2 + \lambda_1\lambda_3}{X_1(X_1 - X_2)}\right]e^{X_1t} \\ & - \left[\frac{\lambda_2\lambda_3 + \mu_2\lambda_1 + \lambda_1\lambda_3}{X_1X_2} + \frac{X_1\lambda_1 + \lambda_2\lambda_3 + \lambda_1\mu_2 + \lambda_1\lambda_3}{X_1(X_1 - X_2)}\right]e^{X_2t} \end{aligned} \tag{10.6}$$

The probability of power plant system degradation due to maintenance error is expressed by Eq. (10.5). As time t becomes very large, Eq. (10.5) reduces to

$$P_1 = \frac{\lambda_2 \mu_1 + \lambda_2 \mu_3 + \lambda_1 \mu_3}{X_1 X_2} \tag{10.7}$$

where

P_1 is the steady-state probability of power plant system degradation due to maintenance error.

The power plant system time-dependent operational availability is expressed by

$$\text{PSOAV}(t) = P_0(t) + P_1(t) \tag{10.8}$$

where

$\text{PSOAV}(t)$ is the power plant system operational availability at time t.

As time t becomes very large, Eq. (10.8) reduces to

$$\text{PSOAV} = \frac{\mu_2 \mu_1 + \lambda_3 \mu_1 + \mu_2 \mu_3 + \lambda_2 \mu_1 + \lambda_2 \mu_3 + \lambda_1 \mu_3}{X_1 X_2} \tag{10.9}$$

where

PSOAV is the power plant system steady-state operational availability.

Example 10.1 Assume that for a power system, the following data values are given:

- $\lambda_1 = 0.005$ failures per hour
- $\mu_1 = 0.04$ repairs per hour
- $\lambda_2 = 0.0003$ failures per hour
- $\mu_2 = 0.007$ repairs per hour
- $\lambda_3 = 0.002$ failures per hour
- $\mu_3 = 0.08$ repairs per hour

Calculate the power plant system degradation steady-state probability due to maintenance error with the aid of Eq. (10.7).

By inserting the specified data values into Eq. (10.7), we obtain

$$\begin{aligned} P_1 = {} & [(0.0003)(0.04) + (0.0003)(0.08) + (0.005)(0.08)]/[(0.007)(0.04) + (0.002)(0.04) \\ & + (0.007)(0.08) + (0.04)(0.0003) + (0.0003)(0.08) + (0.0003)(0.002) \\ & + (0.007)(0.005) + (0.005)(0.08) + (0.005)(0.002)] \\ = {} & 0.3110 \end{aligned}$$

Thus, the power plant system degradation steady-state probability due to maintenance error is 0.3110.

10.7.3 Fault Tree Analysis

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

Example 10.2 A system used in a power plant can fail due to a maintenance error caused by any of the following four factors:

- Carelessness.
- Poor work environment.
- Poor system design.
- Use of poorly written maintenance manuals.

Two major factors for carelessness are time constraints and poor training. Similarly, two factors for poor work environment are distractions and poor lighting.

Develop a fault tree for the top event "power plant system failure due to a maintenance error" by using fault tree symbols given in Chap. 4.

A fault tree for this example is shown in Fig. 10.5.

Example 10.3 Assume that the occurrence probability of each basic event X_1, X_2, X_3, X_4, X_5, and X_6 shown in Fig. 10.5 is 0.02. For independent events, calculate the occurrence probabilities of the top event T (i.e. power plant system failure due to a maintenance error) and intermediate events I_1 (i.e. poor work environment) and I_2 (i.e. carelessness). Also, redraw Fig. 10.5 fault tree with given and calculated fault event occurrence probability values.

With the aid of Chap. 4 and the specified data values, we obtain the values of I_1, I_2, and T as follows:

$$\begin{aligned} P(I_1) &= P(X_1) + P(X_2) - P(X_1)P(X_2) \\ &= 0.02 + 0.02 - (0.02)(0.02) \\ &= 0.0396 \end{aligned} \tag{10.10}$$

where

$P(X_1)$, $P(X_2)$, and $P(I_1)$ are the occurrence probabilities of events X_1, X_2, and I_1, respectively.

The occurrence probability of event I_2 is given by

$$\begin{aligned} P(I_2) &= P(X_3) + P(X_4) - P(X_3)P(X_4) \\ &= 0.02 + 0.02 - (0.02)(0.02) \\ &= 0.0396 \end{aligned} \tag{10.11}$$

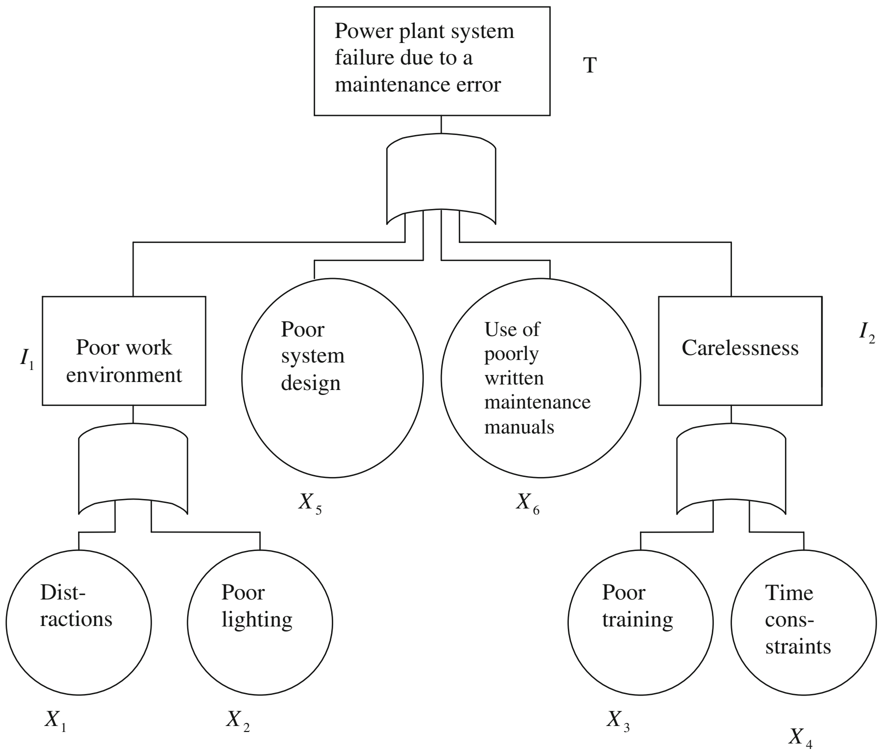


Fig. 10.5 Fault tree for Example 10.2

where

$P(X_3)$, $P(X_4)$, and $P(I_2)$ are the occurrence probabilities of events X_3, X_4, and I_2, respectively.

With the aid of the above calculated and specified data values and Chap. 4, we obtain

$$\begin{aligned} P(T) &= 1 - \{1 - P(I_1)\}\{1 - P(I_2)\}\{1 - P(X_5)\}\{1 - P(X_6)\} \\ &= 1 - (1 - 0.0396)(1 - 0.0396)(1 - 0.02)(1 - 0.02) \\ &= 0.1141 \end{aligned} \tag{10.12}$$

where

$P(T)$, $P(X_5)$, and $P(X_6)$ are the occurrence probabilities of events T, X_5, and X_6, respectively.

Thus, the occurrence probabilities of events T, I_1, and I_2 are 0.1141, 0.0396, and 0.0396, respectively. Figure 10.5 fault tree with given and calculated fault event occurrence probability values is shown in Fig. 10.6.

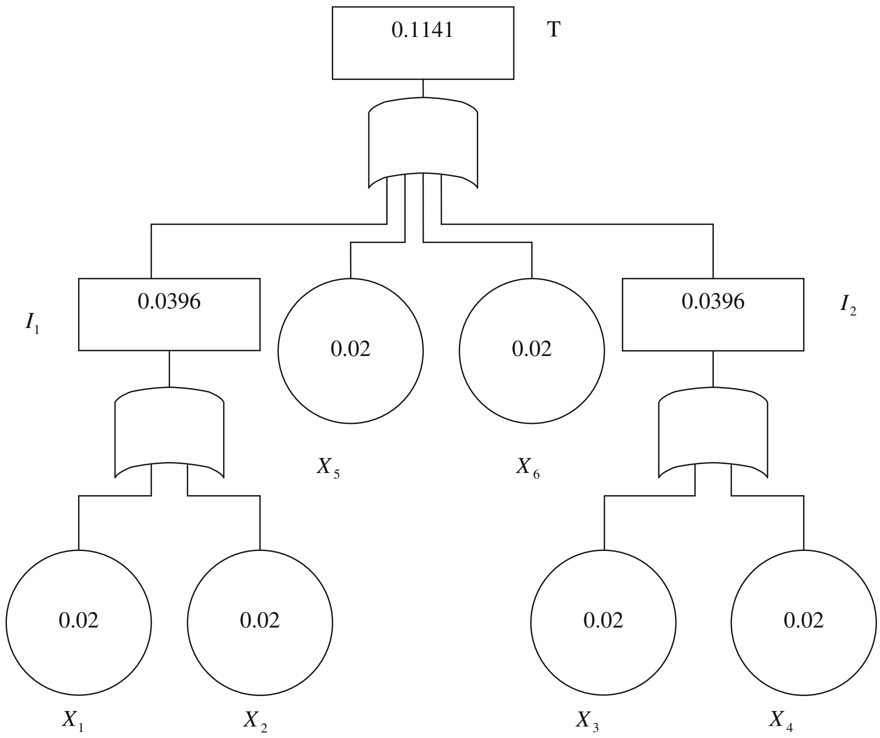


Fig. 10.6 A fault tree with given and calculated fault event occurrence probability values

10.8 Problems

1. Write an essay on human error in power plant maintenance.
2. List at least six facts and figures concerned with human error in power plant maintenance.
3. What are the maintenance tasks in the area of nuclear power generation most susceptible to human error?
4. Discuss the types of human errors in DPPS maintenance tasks.
5. Discuss causal factors for critical incidents and reported events related to maintenance error in power plants.
6. What are the classifications of causes of human errors in power plant maintenance? Discuss each of these classifications.
7. Discuss steps for improving maintenance-related procedures in power plants.
8. Discuss useful guidelines to reduce and prevent human errors in power plant maintenance.
9. What is MAPPS model? Describe it in detail.
10. Prove Eq. (10.7) using Eq. (10.5).

References

1. Dhillon BS (2009) Human reliability, error, and human factors in engineering maintenance. CRC Press, Boca Raton
2. Wu TM, Hwang SL (1989) Maintenance error reduction strategies in nuclear power plants, using root cause analysis. Appl Ergon 20(2):115–121
3. Nuclear power plant operating experiences, from the IAEA/NEA incident reporting system. Organization for Economic Co-operation and Development (OECD), Paris (2000)
4. Reason J (1997) Human Factors in nuclear power generation: a systems perspective. Nucl Europe Worldscan 17(5–6):35–36
5. "An Analysis of 1990 Significant Events", Report No. INPO 91-018, Institute of Nuclear Power Operations (INPO), Atlanta (1991)
6. Heo G, Park J (2009) Framework of quantifying human error effects in testing and maintenance. In: Proceedings of the sixth American nuclear society international topical meeting on nuclear plant instrumentation, control, and human-machine interface technologies, pp 2083–2092
7. Hasegawa T, Kameda A (1998) Analysis and evaluation of human error events in nuclear power plants. Presented at the Meeting of the IAEA's CRP on "collection and classification of human reliability data for use in probabilistic safety assessments", May 1998. Available from the Institute of Human Factors, Nuclear Power Engineering Corporation, 3-17-1, Toranomon, Minato-Ku, Tokyo, Japan
8. Maintenance Error a Factor in Blackouts, Miami Herald, 29 Dec 1989, p 4
9. Daniels RW (1985) The formula for improved plant maintainability must include human factors. In: Proceedings of the IEEE conference on human factors and nuclear safety, pp 242–244
10. The UAW and the rouge explosion: a pat on the head, Detroit News, Detroit, 6 Feb 1999, p 6
11. White J (2000) New revelations expose company-union complicity in Fatal Blast at US Ford Plant. http://www.wsws.org/articles/2000/feb2000/ford-fo4.shtml
12. Pyy P, Laakso K, Reiman L (1997) A study of human errors related to NPP maintenance activities. In: Proceedings of the IEEE 6th annual human factors meeting, pp 1223–1228
13. Pyy P (2001) An analysis of maintenance failures at a nuclear power plant. Reliab Eng Syst Saf 72:293–302
14. Isoda H, Yasutake JY (1992) Human factors interventions to reduce human errors and improve productivity in maintenance tasks. In: Proceedings of the international conference on design and safety of advanced nuclear power plants, pp 3441–3446
15. Khalaquzzaman M, Kang HG, Kim MC, Seong PH (2010) A Model for estimation of reactor spurious shutdown rate considering maintenance human errors in reactor protection system of nuclear power plants. Nucl Eng Des 240:2963–2971
16. DPPS Maintenance Manual, Ulchin Nuclear Power Plant Unit No. 586, Document No. 9-650-Z-431-100, Westinghouse Corporation, Butler County, Pennsylvania (2002)
17. Seminara JL, Persons SO (1981) Human factors review of power plant maintainability. Report No. NP-1567 (Research Project 1136), Electric Power Research Institute, Palo Alto
18. Seminara JL, Persons SO (1985) Human factors engineering and power plant maintenance. Maintenance Manage Int 6:33–71
19. Herrin JL, Heuertz SW (1988) Improving maintenance procedures: one utility's perspectives. In: Proceedings of the IEEE conference on human factors and power plants, pp 373–377
20. Knee HE (1988) The maintenance personnel performance simulation (MAPPS) model: a human reliability analysis tool. In: Proceedings of the international conference on nuclear power plant aging, availability factors, and power plants, pp 373–377
21. Dhillon BS (1983) Power system reliability, safety, and management. Ann Arbor Science Publishers, Ann Arbor
22. Dhillon BS, Singh C (1981) Engineering reliability: new techniques and applications. Wiley, New York

Chapter 11
Mathematical Models for Performing Human Reliability and Error Analysis in Power Plants

11.1 Introduction

Mathematical modelling is a widely used approach in the area of engineering to perform various types of analysis. In this case, a system's components are represented by idealized elements assumed to have representative characteristics of real-life components, and whose behaviour is possible to be described by equations. However, the degree of realism of a mathematical model very much depends on the assumptions imposed upon it.

Over the years, in the area of reliability engineering, a large number of mathematical models have been developed to study various aspects of human reliability and error in engineering systems. Most of these models were developed using the Markov method [1–3]. Although, the effectiveness of such models can vary from one situation to another, some of these models are being used quite successfully to study various types of real-life environments in industry [4–6]. Thus, some of these models can also be used to study human reliability and error-related problems in the area of power generation.

This chapter presents the mathematical models considered most useful for performing human reliability and error analysis in power plants.

11.2 Model I: Human Correctability Probability Function

This mathematical model is concerned with the human capacity to correct self-generated errors. More specifically, the model is concerned with predicting the probability that a self-generated error will be corrected in time t. Nonetheless, Ref. [2] defines correctability function as the probability that a task will be corrected in time t subjected to stress constraint related to the task and its environments. Mathematically, the correctability probability function is expressed as follows [2, 5, 7, 8]:

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6_11,

$$\mathrm{CP}(t) = P\,(\text{correction of error in time } t/\text{stress}) \tag{11.1}$$

where

$\mathrm{CP}(t)$ is the probability that a human error will be corrected/rectified in time t.

P is the probability.

The time derivative of non-correctability probability function, $\overline{\mathrm{CP}}(t)$, is expressed by [2]

$$\overline{\mathrm{CP}}'(t) = -\frac{1}{n}\mathrm{NC}'(t) \tag{11.2}$$

where the prime denotes differentiation with respect to time t, and

$\mathrm{NC}(t)$ is the number of times the task is not accomplished after time t.

n is the number of times task correction is accomplished after time t.

By dividing the both sides of Eq. (11.2) by $\mathrm{NC}(t)$, and rearranging, we obtain

$$\frac{\overline{\mathrm{CP}}'(t)\cdot n}{\mathrm{NC}(t)} = -\frac{\mathrm{NC}'(t)}{\mathrm{NC}(t)} \tag{11.3}$$

The right-hand side of Eq. (11.3) represents the instantaneous task correction rate, $\alpha_c(t)$. Hence, with the aid of Eq. (11.1), we rewrite Eq. (11.3) as follows [8]:

$$\frac{\overline{\mathrm{CP}}'(t)}{\overline{\mathrm{CP}}(t)} + \alpha_c(t) = 0 \tag{11.4}$$

By solving Eq. (11.4) for specified initial conditions, we obtain

$$\overline{\mathrm{CP}}(t) = e^{-\int_0^t \alpha_c(t)\mathrm{d}t} \tag{11.5}$$

Since $\mathrm{CP}(t) + \overline{\mathrm{CP}}(t) = 1$, we get

$$\mathrm{CP}(t) = 1 - e^{-\int_0^t \alpha_c(t)\mathrm{d}t} \tag{11.6}$$

It is to be noted that Eq. (11.6) is a general expression for correctability probability function (i.e. it holds for both constant or non-constant task correction rates). More specifically, it holds whether the task correction times are described by the exponential distribution or any other probability distribution such as Weibull.

Example 11.1 A power plant operator's self-generated error correction times are Weibull distributed. Thus, his/her task/error correction rate is defined by

$$\alpha_c(t) = \frac{ct^{c-1}}{\beta^c} \tag{11.7}$$

where

c is the distribution shape parameter.

β is the distribution scale parameter.

t is time.

Obtain an expression for the correctability probability function of the operator.

By inserting Eq. (11.7) into Eq. (11.6), we obtain

$$\begin{aligned} \mathrm{CP}(t) &= 1 - e^{-\int_0^t ((ct^{c-1})/\beta^c)\mathrm{d}t} \\ &= 1 - e^{-(t/\beta)^c} \end{aligned} \tag{11.8}$$

Thus, Eq. (11.8) is the expression for the correctability probability function of the power plant operator.

11.3 Model II: Critical and Non-Critical Human Errors Probability Prediction

This mathematical model represents an operator or any other personnel in power plants performing a time-continuous task subjected to non-critical and critical errors. More specifically, the errors committed by these personnel are grouped under two categories (i.e. non-critical and critical). The model can be used to obtain information such as the following:

- The power plant operator mean time to error.
- The power plant operator performance reliability at time t.
- The probability of the power plant operator committing a non-critical error at time t.
- The probability of the power plant operator committing a critical error.

The state space diagram of the model is shown in Fig. 11.1, and the numerals in the diagram circle and boxes denote the states of the power plant operator.

The model is subjected to the following assumptions:

- Non-critical human error rate is constant.
- Critical human error rate is constant.
- Human errors occur independently.

The following symbols are associated with the model/diagram:

i is the ith state of the power plant operator; $i = 0$ means that the power plant operator is performing his/her task correctly; $i = 1$ means that the power plant operator has committed a critical human error; and $i = 2$ means that the power plant operator has committed a non-critical human error.

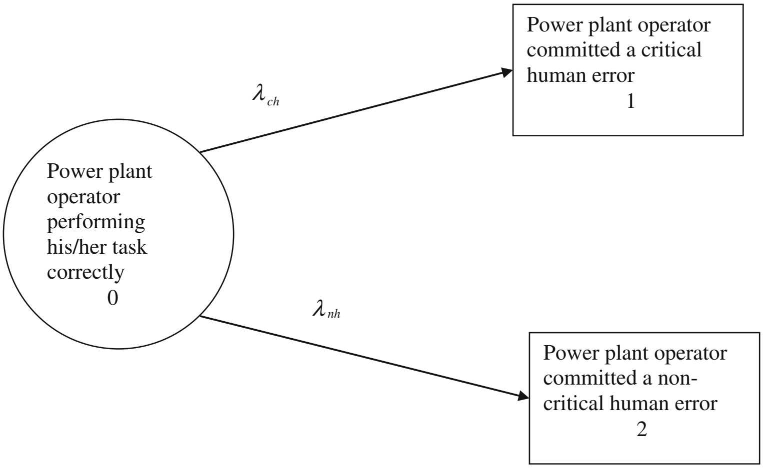


Fig. 11.1 State space diagram for the power plant operator subjected to non-critical and critical human errors

$P_i(t)$ is the probability of the power plant operator being in state i at time t, for $i = 0,\ 1,\ 2$.
λ_{ch} is the constant critical human error rate of the power plant operator.
λ_{nh} is the constant non-critical human error rate of the power plant operator.

Using the Markov method, we write down the following equations for the Fig. 11.1 diagram [1, 9, 10]:

$$\frac{\mathrm{d}P_0(t)}{\mathrm{d}t} + (\lambda_{\mathrm{nh}} + \lambda_{\mathrm{ch}})P_0(t) = 0 \tag{11.9}$$

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} - \lambda_{\mathrm{ch}}P_0(t) = 0 \tag{11.10}$$

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} - \lambda_{\mathrm{nh}}P_0(t) = 0 \tag{11.11}$$

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

Solving Eqs. (11.9–11.11), we get the following equations.

$$P_0(t) = e^{-(\lambda_{\mathrm{nh}}+\lambda_{\mathrm{ch}})t} \tag{11.12}$$

$$P_1(t) = \frac{\lambda_{\mathrm{ch}}}{\lambda_{\mathrm{nh}} + \lambda_{\mathrm{ch}}}\left[1 - e^{-(\lambda_{\mathrm{nh}}+\lambda_{\mathrm{ch}})t}\right] \tag{11.13}$$

$$P_2(t) = \frac{\lambda_{\mathrm{nh}}}{\lambda_{\mathrm{nh}} + \lambda_{\mathrm{ch}}}\left[1 - e^{-(\lambda_{\mathrm{nh}}+\lambda_{\mathrm{ch}})t}\right] \tag{11.14}$$

The reliability of the power plant operator's performance is given by

$$\begin{aligned} R_{\mathrm{po}}(t) &= P_0(t) \\ &= e^{-(\lambda_{\mathrm{nh}}+\lambda_{\mathrm{ch}})t} \end{aligned} \tag{11.15}$$

where

$R_{\mathrm{po}}(t)$ is the reliability of the power plant operator's performance at time t.

Mean time to human error of the power plant operator is given by Dhillon [1, 10]

$$\begin{aligned} \mathrm{MTTHE}_{\mathrm{po}} &= \int_0^\infty R_{po}(t)\,\mathrm{d}t \\ &= \int_0^\infty e^{-(\lambda_{\mathrm{nh}}+\lambda_{\mathrm{ch}})t}\,\mathrm{d}t \\ &= \frac{1}{\lambda_{\mathrm{nh}}+\lambda_{\mathrm{ch}}} \end{aligned} \tag{11.16}$$

where

$\mathrm{MTTHE}_{\mathrm{po}}$ is the mean time to human error of the power plant operator.

Example 11.2 Assume that a power plant operator's constant non-critical and critical human error rates are 0.0008 and 0.0003 errors/h, respectively. Calculate the power plant operator's mean time to human error and probability of making a critical human error during a 10-h mission.

Substituting the given data values into Eqs. (11.16) and (11.13) yields

$$\begin{aligned} \mathrm{MTTHE}_{\mathrm{po}} &= \frac{1}{0.0008+0.0003} \\ &= 909.09\,\mathrm{h} \end{aligned}$$

and

$$\begin{aligned} P_1(10) &= \frac{0.0003}{0.0008+0.0003}\left[1-e^{-(0.0008+0.0003)(10)}\right] \\ &= 0.0029 \end{aligned}$$

Thus, the power plant operator's mean time to human error and probability of making a critical human error during a 10-h mission are 909.09 h and 0.0029, respectively.

11.4 Model III: Human Performance Reliability in Fluctuating Environment

This mathematical model represents a power plant operator or any other power plant personnel performing time-continuous task in fluctuating environment (i.e. normal and stressful). As the rate of human errors can vary significantly from normal work environment to stressful work environment, this mathematical model can be used to calculate the power plant operator's performance reliability, probabilities of making an error in normal and stressful environments, and mean time to human error in the fluctuating environment.

The state space diagram of this mathematical model is shown in Fig. 11.2, and the numerals in the diagram boxes denote the states of the power plant operator.

The following assumptions are associated with the model:

- Rates of the environment changing from normal to stressful and vice versa are constant.
- All power plant operator errors occur independently.
- Power plant operator error rates in normal and stressful environments are constant.

The following symbols are associated with the diagram/model:

i is the ith state of the power plant operator; $i = 0$ means that the power plant operator is performing his/her task correctly in normal environment; $i = 1$ means that the power plant operator is performing his/her task correctly in stressful environment; $i = 2$ means that the power plant operator has committed an error in normal environment; and $i = 3$ means that the power plant operator has committed an error in stressful environment.

$P_i(t)$ is the probability of the power plant operator being in state i at time t, for $i = 0, 1, 2, 3$.

α_s is the constant transition rate from normal work environment to stressful work environment.

α_n is the constant transition rate from stressful work environment to normal work environment.

λ_{hs} is the constant human error rate of the power plant operator performing his/her task in stressful environment.

λ_{hn} is the constant human error rate of the power plant operator performing his/her task in normal environment.

With the aid of Markov method, we write down the following set of equations for the Fig. 11.2 diagram [3, 10]:

$$\frac{dP_0(t)}{dt} + (\lambda_{hn} + \alpha_s)P_0(t) = \alpha_n P_1(t) \tag{11.17}$$

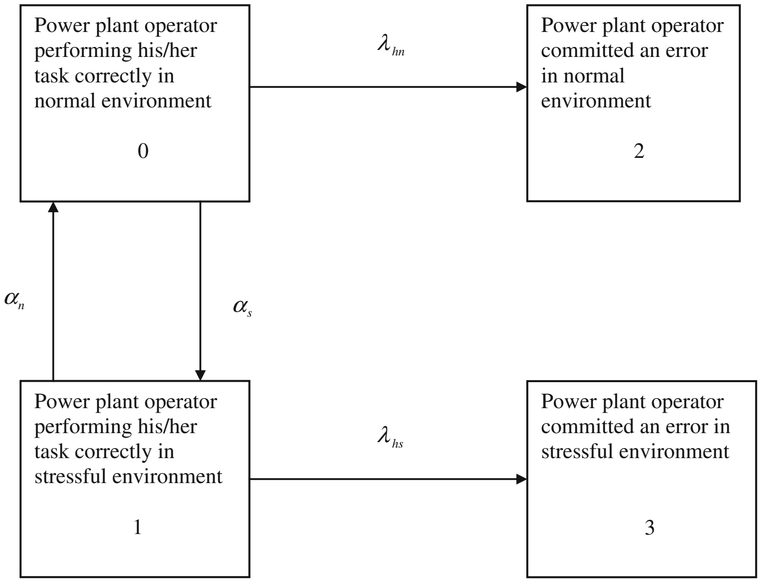


Fig. 11.2 State space diagram for the power plant operator performing his/her task in fluctuating normal and stressful environments

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} + (\lambda_{\mathrm{hs}} + \alpha_n)P_1(t) = \alpha_s P_0(t) \tag{11.18}$$

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} = \lambda_{\mathrm{hn}} P_0(t) \tag{11.19}$$

$$\frac{\mathrm{d}P_3(t)}{\mathrm{d}t} = \lambda_{\mathrm{hs}} P_1(t) \tag{11.20}$$

At time $t = 0$, $P_0(0) = 1$, and, $P_1(0) = P_2(0) = P_3(0) = 0$.

By solving Eqs. (11.17–11.20) with the aid of Laplace transforms, we obtain the following state probability equations:

$$P_0(t) = \frac{1}{(y_1 - y_2)}\left[(y_2 + \lambda_{\mathrm{hs}} + \alpha_n)e^{y_2 t} - (y_1 + \lambda_{\mathrm{hs}} + \alpha_n)e^{y_1 t}\right] \tag{11.21}$$

where

$$y_1 = \left[-a_1 + (a_1^2 - 4a_2)^{1/2}\right]/2 \tag{11.22}$$

$$y_2 = \left[-a_1 - (a_1^2 - 4a_2)^{1/2}\right]/2 \tag{11.23}$$

$$a_1 = \lambda_{\mathrm{hn}} + \lambda_{\mathrm{hs}} + \alpha_n + \alpha_s \tag{11.24}$$

$$a_2 = \lambda_{\text{hn}}(\lambda_{\text{hs}} + \alpha_n) + \alpha_s\lambda_{\text{hs}} \tag{11.25}$$

$$P_2(t) = a_4 + a_5 e^{y_2 t} - a_6 e^{y_1 t} \tag{11.26}$$

where

$$a_3 = \frac{1}{y_2 - y_1} \tag{11.27}$$

$$a_4 = \lambda_{\text{hn}}(\lambda_{\text{hs}} + \alpha_n)/y_1 y_2 \tag{11.28}$$

$$a_5 = a_3(\lambda_{\text{hn}} + a_4 y_1) \tag{11.29}$$

$$a_6 = a_3(\lambda_{\text{hn}} + a_4 y_2) \tag{11.30}$$

$$P_1(t) = \alpha_s a_3(e^{y_2 t} - e^{y_1 t}) \tag{11.31}$$

$$P_3(t) = a_7[(1 + a_3)(y_1 e^{y_2 t} - y_2 e^{y_1 t})] \tag{11.32}$$

where

$$a_7 = \lambda_{\text{hs}}\alpha_s/y_1 y_2 \tag{11.33}$$

The performance reliability of the power plant operator is given by

$$R_{\text{ppo}}(t) = P_0(t) + P_1(t) \tag{11.34}$$

where
$R_{\text{ppo}}(t)$ is the power plant operator reliability at time t.

The mean time to human error of the power plant operator is given by

$$\begin{aligned} \text{MTTHE}_{\text{ppo}} &= \int_0^\infty R_{\text{ppo}}(t)\text{d}t \\ &= (\lambda_{\text{hs}} + \alpha_s + \alpha_n)/a_2 \end{aligned} \tag{11.35}$$

where
$\text{MTTHE}_{\text{ppo}}$ is the mean time to human error of the power plant operator.

Example 11.3 Assume that an operator is performing a certain task at a power plant in fluctuating environments and his/her constant error rates in normal and stressful environments are 0.0002 and 0.0004 errors/h, respectively. The constant transition rates from normal to stressful environment and vice versa are 0.05 and 0.01 times/h, respectively.

Calculate the mean time to human error of the power plant operator.

By inserting the given data values into Eq. (11.35), we obtain

$$\text{MTTHE}_{\text{ppo}} = \frac{(0.0004 + 0.05 + 0.01)}{(0.0002)(0.0004 + 0.01) + (0.05)(0.0004)}$$
$$= 2{,}735.51\,\text{h}$$

Thus, the mean time to human error of the power plant operator is 2,735.51 h.

11.5 Model IV: Human Performance Reliability Prediction with Critical and Non-Critical Self-Generated Errors and Corrective Action

This mathematical model is the same as Model II but with one exception, i.e. the corrective action is taken by the power plant operator from states 1 and 2 as shown in Fig. 11.3 state space diagram. The additional symbols shown in the state space diagram are μ_{ch} and μ_{nh}, representing the power plant operator's constant critical human error correction rate and constant non-critical human error correction rate, respectively. All other symbols and assumptions used in this model are same as the ones in Model II.

With the aid of Markov method, we write down the following equations for Fig. 11.3 state space diagram [9, 10]:

$$\frac{\mathrm{d}P_0(t)}{\mathrm{d}t} + (\lambda_{ch} + \lambda_{nh})P_0(t) = \mu_{ch}P_1(t) + \mu_{nh}P_2(t) \tag{11.36}$$

$$\frac{\mathrm{d}P_1(t)}{\mathrm{d}t} + \mu_{ch}P_1(t) = \lambda_{ch}P_0(t) \tag{11.37}$$

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} + \mu_{nh}P_2(t) = \lambda_{nh}P_0(t) \tag{11.38}$$

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

Solving Eqs. (11.36–11.38), we obtain the following equations:

$$P_0(t) = \frac{\mu_{ch}\mu_{nh}}{x_1x_2} + \left[\frac{(x_1 + \mu_{nh})(x_1 + \mu_{ch})}{x_1(x_1 - x_2)}\right]e^{x_1t} - \left[\frac{(x_2 + \mu_{nh})(x_2 + \mu_{ch})}{x_2(x_1 - x_2)}\right]e^{x_2t} \tag{11.39}$$

where

$$x_1, x_2 = \frac{-b \pm \left(b^2 - 4(\mu_{ch}\mu_{nh} + \lambda_{ch}\mu_{nh} + \lambda_{nh}\mu_{ch})\right)^{1/2}}{2} \tag{11.40}$$

$$b = \lambda_{ch} + \lambda_{nh} + \mu_{ch} + \mu_{nh} \tag{11.41}$$

$$x_1x_2 = \mu_{ch}\mu_{nh} + \lambda_{nh}\mu_{ch} + \lambda_{ch}\mu_{nh} \tag{11.42}$$

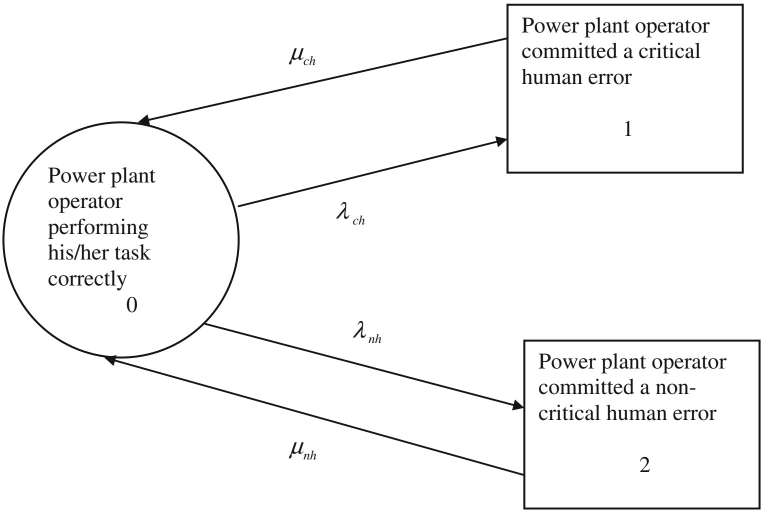


Fig. 11.3 State space diagram for the power plant operator subjected to non-critical and critical human errors and corrections

$$x_1 + x_2 = -(\mu_{\mathrm{ch}} + \mu_{\mathrm{nh}} + \lambda_{\mathrm{ch}} + \lambda_{\mathrm{nh}}) \tag{11.43}$$

$$P_1(t) = \frac{\lambda_{\mathrm{ch}}\mu_{\mathrm{nh}}}{x_1 x_2} + \left[\frac{\lambda_{\mathrm{ch}} x_1 + \lambda_{\mathrm{ch}}\mu_{\mathrm{nh}}}{x_1(x_1 - x_2)}\right] e^{x_1 t} - \left[\frac{((\mu_{\mathrm{nh}} + x_2)\lambda_{\mathrm{ch}})}{x_2(x_1 - x_2)}\right] e^{x_2 t} \tag{11.44}$$

$$P_2(t) = \frac{\lambda_{\mathrm{nh}}\mu_{\mathrm{ch}}}{x_1 x_2} + \left[\frac{\lambda_{\mathrm{nh}} x_1 + \lambda_{\mathrm{nh}}\mu_{\mathrm{ch}}}{x_1(x_1 - x_2)}\right] e^{x_1 t} - \left[\frac{(\mu_{\mathrm{ch}} + x_2)\lambda_{\mathrm{nh}}}{x_2(x_1 - x_2)}\right] e^{x_2 t} \tag{11.45}$$

Thus, the power plant operator's performance reliability with correction is expressed by Eq. (11.39), i.e.

$$R_{\mathrm{pc}}(t) = P_0(t) \tag{11.46}$$

where

$R_{\mathrm{pc}}(t)$ is the power plant operator's performance reliability with correction at time t.

As time t becomes very large, we obtain the following steady-state probability equations from Eqs. (11.39), (11.44), and (11.45), respectively:

$$P_0 = \lim_{t \to \infty} P_0(t) = \frac{\mu_{\mathrm{ch}}\mu_{\mathrm{nh}}}{x_1 x_2} \tag{11.47}$$

$$P_1 = \lim_{t \to \infty} P_1(t) = \frac{\lambda_{\mathrm{ch}}\mu_{\mathrm{nh}}}{x_1 x_2} \tag{11.48}$$

$$P_2 = \lim_{t \to \infty} P_2(t) = \frac{\lambda_{nh}\mu_{ch}}{x_1 x_2} \quad (11.49)$$

where

P_j is the power plant operator's steady-state probability being in state j; for $j = 0, 1, 2$.

Example 11.4 A power plant operator is performing a time-continuous task, and during an accumulated period of 12,000 h, he/she made a total of 12 non-critical errors and self-corrected five of them. During the same time period, he/she also made four critical human errors and self-corrected one of them. More specifically, the operator took 3 h to correct five non-critical errors and 2 h to correct one critical error.

Calculate the power plant operator's steady-state probabilities of being in states 0, 1, and 2, if the times to error correction and the times to error are exponentially distributed.

For the given data values, we get

$$\lambda_{nh} = \frac{12}{12{,}000} = 0.001 \text{ errors/h}$$

$$\lambda_{ch} = \frac{4}{12{,}000} = 0.0003 \text{ errors/h}$$

$$\mu_{nh} = \frac{5}{3} = 1.67 \text{ corrections/h}$$

$$\mu_{ch} = \frac{1}{2} = 0.5 \text{ corrections/h}$$

By inserting the above-calculated values into Eqs. (11.47–11.49), we obtain:

$$P_0 = \frac{(0.5)(1.67)}{(0.5)(1.67) + (0.001)(0.5) + (0.0003)(1.67)} = 0.9988$$

$$P_1 = \frac{(0.0003)(1.67)}{(0.5)(1.67) + (0.001)(0.5) + (0.0003)(1.67)} = 0.0006$$

$$P_2 = \frac{(0.001)(0.5)}{(0.5)(1.67) + (0.001)(0.5) + (0.0003)(1.67)} = 0.0006$$

Thus, the steady-state probabilities of the power plant operator being in states 0, 1, and 2 are 0.9988, 0.0006, and 0.0006, respectively.

11.6 Model V: Availability Analysis of a Power Plant System with Human Error

This mathematical model represents a power plant system that can only fail due to the occurrence of hardware failures, but human errors made by power plant personnel can degrade its performance. The system is repaired from degraded and failed states.

The state space diagram of this mathematical model is shown in Fig. 11.4, and the numerals in the diagram circles and box denote the states of the power plant system. The model is subjected to the following assumptions:

- Power plant system hardware failure and human error rates are constant.
- The degraded power plant system can only fail due to hardware failures.
- Human errors made by power plant personnel can only lead to power plant system degradation, but not failure.
- All power plant system repair rates are constant.
- The repaired power plant system is as good as new.
- The completely or partially failed power plant system is repaired.
- The completely failed power plant system is repaired either to its degraded state or to its normal working state.

The following symbols are associated with the model/diagram:

i is the ith state of the power plant system; $i = 0$ means that the power plant system is working normally; $i = 1$ means that the power plant system degraded due to human error made by power plant personnel; and $i = 3$ means that the power plant system failed.

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

λ_s is the power plant system constant failure rate.

μ_s is the power plant system constant repair rate.

λ_h is the constant human error rate due to power plant personnel.

μ_d is the constant repair rate from the power plant system degraded state to normal working state.

λ is the power plant system constant failure rate from its degraded state.

μ is the constant repair rate from the power plant system failed state to degraded or partially working state.

With the aid of Markov method, we write down the following set of equations for the Fig. 11.4 state space diagram [1, 10, 11]:

$$\frac{dP_0(t)}{dt} + (\lambda_h + \lambda_s)P_0(t) = \mu_d P_1(t) + \mu_s P_2(t) \tag{11.50}$$

$$\frac{dP_1(t)}{dt} + (\lambda + \mu_d)P_1(t) = \lambda_h P_0(t) + \mu P_2(t) \tag{11.51}$$

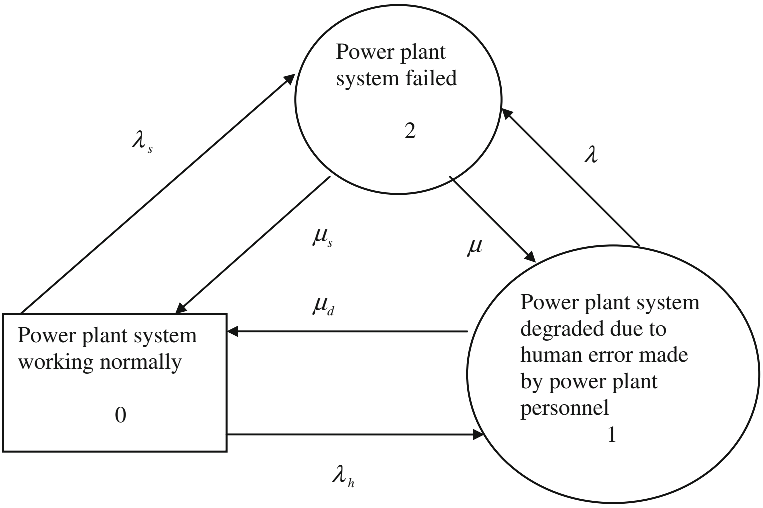


Fig. 11.4 State space diagram for the power plant system

$$\frac{\mathrm{d}P_2(t)}{\mathrm{d}t} + (\mu + \mu_s)P_2(t) = \lambda_s P_0(t) + \lambda P_1(t) \tag{11.52}$$

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

Solving Eqs. (11.50–11.52), we obtain the following equations:

$$\begin{aligned} P_0(t) = {} & \frac{\mu_d\mu_s + \lambda\mu_s + \mu_d\mu}{B_1B_2} + \left[\mu_d B_1 + \mu_s B_1 + \mu B_1 + \lambda B_1 + B_1^2 + \mu_d\mu_s + \lambda\mu_s + \mu_d\mu\right]e^{B_1 t} \\ & + \left\{1 - \left(\frac{\mu_d\mu_s + \lambda\mu_s + \mu_d\mu}{B_1B_2}\right) - \left[\frac{\mu_d B_1 + \mu_s B_1 + \mu B_1 + B_1\lambda + B_1^2 + \mu_d\mu_s + \lambda\mu_s + \mu_d\mu}{B_1(B_1 - B_2)}\right]\right\}e^{B_2 t} \end{aligned} \tag{11.53}$$

where

$$B_1,\, B_2 = \frac{\left[-C \pm \{C_2 - 4(\mu_d\mu_s + \lambda\mu_s + \mu_d\mu + \mu_s\lambda_h + \lambda_h\mu + \lambda_h\lambda + \mu_d\lambda_s + \lambda_s\mu + \lambda_s\lambda)\}^{1/2}\right]}{2} \tag{11.54}$$

$$C = \lambda_h + \lambda_s + \lambda + \mu + \mu_s + \mu_d \tag{11.55}$$

$$B_1B_2 = \mu_d\mu_s + \lambda\mu_s + \mu_d\mu + \mu_s\lambda_h + \lambda_h\mu + \lambda_h\lambda + \mu_d\lambda_s + \lambda_s\mu + \lambda_s\lambda \tag{11.56}$$

$$\begin{aligned} P_1(t) = {} & \frac{\lambda_h\mu_s + \lambda_h\mu + \lambda_s\mu}{B_1B_2} + \left[\frac{B_1\lambda_h + \lambda_h\mu_s + \lambda_h\mu + \lambda_s\mu}{B_1(B_1 - B_2)}\right]e^{B_1 t} \\ & - \left[\frac{\lambda_h\mu_s + \lambda_h\mu + \lambda_s\mu}{B_1B_2} + \frac{B_1\lambda_h + \lambda_h\mu_s + \lambda_h\mu + \lambda_s\mu}{B_1(B_1 - B_2)}\right]e^{B_2 t} \end{aligned} \tag{11.57}$$

$$P_2(t) = \frac{\lambda_h\lambda + \mu_d\lambda_s + \lambda_s\lambda}{B_1B_2} + \left[\frac{B_1\lambda_s + \lambda_h\lambda + \lambda_s\mu_d + \lambda_s\lambda}{B_1(B_1 - B_2)}\right]e^{B_1t} - \left[\frac{\lambda_h\lambda + \mu_d\lambda_s + \lambda_s\lambda}{B_1B_2} + \frac{B_1\lambda_s + \lambda_h\lambda + \lambda_s\mu_d + \lambda_s\lambda}{B_1(B_1 - B_2)}\right]e^{B_2t} \tag{11.58}$$

The probability of the power plant system degradation due to human error by the power plant personnel is expressed by Eq. (11.57). As time t becomes very large, Eq. (11.57) reduces to

$$P_1 = \frac{\lambda_h\mu_s + \lambda_h\mu + \lambda_s\mu}{B_1B_2} \tag{11.59}$$

where

P_1 is the steady-state probability of the power plant system degradation due to human error by the power plant personnel.

The power plant system operational availability at time t is expressed by

$$\mathrm{AV}_{\mathrm{ps}}(t) = P_0(t) + P_1(t) \tag{11.60}$$

where

$\mathrm{AV}_{\mathrm{ps}}(t)$ is the power plant system operational availability at time t.

As time t becomes very large, with the aid of Eqs. (11.53) and (11.57), Eq. (11.60) becomes

$$\mathrm{AV}_{\mathrm{ps}} = \frac{\mu_d\mu_s + \lambda\mu_s + \mu_d\mu + \lambda_h\mu_s + \lambda_h\mu + \lambda_s\mu}{B_1B_2} \tag{11.61}$$

where

$\mathrm{AV}_{\mathrm{ps}}$ is the power plant system steady-state operational availability.

Example 11.5 Assume that for a certain power plant system, the following data values are known:

$$\lambda_h = 0.0005 \text{ errors/h}$$
$$\lambda_s = 0.004 \text{ failures/h}$$
$$\lambda = 0.001 \text{ failures/h}$$
$$\mu = 0.07 \text{ repairs/h}$$
$$\mu_s = 0.06 \text{ repairs/h}$$
$$\mu_d = 0.008 \text{ repairs/h}$$

Calculate the steady-state probability of the power plant system degradation due to human error by the power plant personnel.

By inserting the given data values into Eq. (11.59), we get

$$
\begin{aligned}
P_1 &= [(0.0005)(0.06) + (0.0005)(0.07) + (0.004)(0.07)]/[(0.008)(0.006) \\
&\quad + (0.001)(0.06) + (0.008)(0.07) + (0.06)(0.0005) + (0.0005)(0.07) \\
&\quad + (0.0005)(0.001) + (0.008)(0.004) + (0.004)(0.07) + (0.004)(0.001)] \\
&= \frac{0.000345}{0.001481} = 0.2328
\end{aligned}
$$

Thus, the steady-state probability of the power plant system degradation due to human error by the power plant personnel is 0.2328.

11.7 Model VI: Reliability Analysis of a Power Plant Redundant System with Human Errors

This mathematical model represents a two-identical redundant active unit power plant system subjected to the occurrence of human errors. Each of these units can fail either due to a human error or due to a hardware failure. For the successful operation of the power plant system, at least one unit must operate normally.

The state space diagram of the power plant system is shown in Fig. 11.5, and the numerals in the circle and boxes denote system states.

The following assumptions are associated with the model:

- Both the system units are identical and operate simultaneously.
- Each unit can fail either due to a human error or hardware failure.
- Failures of each unit can be categorized under two classifications: failures due to human errors and failures due to hardware problems.
- Human errors and hardware failures occur independently.
- Human error and hardware failure rates are constant.

The following symbols are associated with the model/diagram:

j is the jth state of the power plant system; $j = 0$ (both units of the power plant system operating normally); $j = 1$ (one unit failed due to a hardware failure, the other working normally); $j = 2$ (one unit failed due to a human error, the other working normally); $j = 3$ (both units failed due to hardware failures); and $j = 4$ (both units failed due to human errors).

$P_j(t)$ is the probability that the power plant system is in state j at time t, for $j = 0, 1, 2, 3, 4$.

α_u is the constant human error rate of a unit.

λ_u is the constant hardware failure rate of a unit.

With the aid of Markov method, we write down the following set of equations for the Fig. 11.5 diagram [1]:

$$\frac{dP_0(t)}{dt} + (2\lambda_u + 2\alpha_u)P_0(t) = 0 \tag{11.62}$$

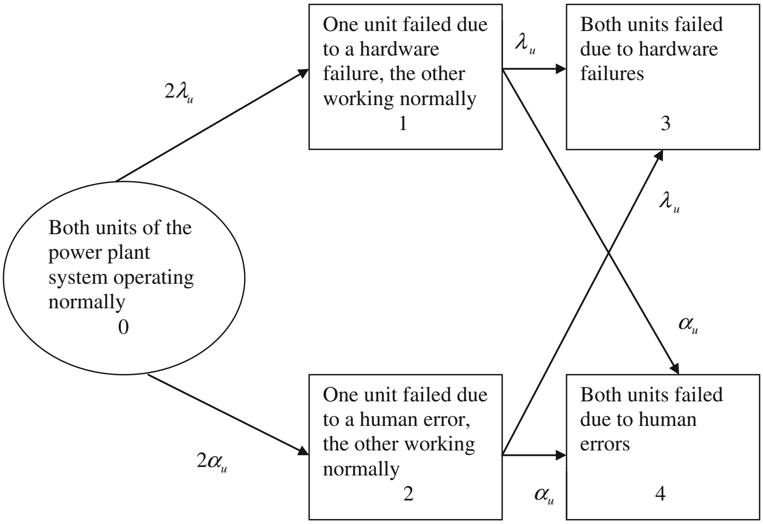


Fig. 11.5 State space diagram of a two-redundant unit power plant system

$$\frac{dP_1(t)}{dt} + (\lambda_u + \alpha_u)P_1(t) = 2\lambda_u P_0(t) \tag{11.63}$$

$$\frac{dP_2(t)}{dt} + (\lambda_u + \alpha_u)P_2(t) = 2\alpha_u P_0(t) \tag{11.64}$$

$$\frac{dP_3(t)}{dt} = \lambda_u P_1(t) + \lambda_u P_2(t) \tag{11.65}$$

$$\frac{dP_4(t)}{dt} = \alpha_u P_1(t) + \alpha_u P_2(t) \tag{11.66}$$

At time $t = 0$, $P_0(0) = 1$, and $P_1(0) = P_2(0) = P_3(0) = P_4(0) = 0$.

Solving Eqs. (11.62–11.66), we obtain the following equations for the power plant system state probabilities:

$$P_0(t) = e^{-2(\lambda_u + \alpha_u)t} \tag{11.67}$$

$$P_1(t) = \frac{2\lambda_u}{(\lambda_u + \alpha_u)}\left[e^{-(\lambda_u + \alpha_u)t} - e^{-2(\lambda_u + \alpha_u)t}\right] \tag{11.68}$$

$$P_2(t) = \frac{2\alpha_u}{(\lambda_u + \alpha_u)}\left[e^{-(\lambda_u + \alpha_u)t} - e^{-2(\lambda_u + \alpha_u)t}\right] \tag{11.69}$$

$$P_3(t) = \frac{\lambda_u}{(\lambda_u + \alpha_u)}\left[1 - e^{-(\lambda_u + \theta_u)t}\right]^2 \tag{11.70}$$

$$P_4(t) = \frac{\alpha_u}{\lambda_u + \alpha_u}\left[1 - e^{(\lambda_u+\alpha_u)t}\right]^2 \quad (11.71)$$

The power plant system reliability is expressed by

$$\begin{aligned} R_{ps}(t) &= P_0(t) + P_1(t) + P_2(t) \\ &= 1 - \left[1 - e^{-(\lambda_u+\alpha_u)t}\right]^2 \end{aligned} \quad (11.72)$$

where
$R_{ps}(t)$ is the reliability of the power plant system at time t.

By integrating Eq. (11.72) over the time interval $[0, \infty]$, we obtain [10]:

$$\begin{aligned} \mathrm{MTTF}_{ps} &= \int_0^\infty R_{ps}(t)\mathrm{d}t \\ &= \frac{3}{2(\lambda_u + \alpha_u)} \end{aligned} \quad (11.73)$$

where
MTTF_{ps} is the mean time to failure of a two-redundant active unit power plant system with human error.

Example 11.6 Assume that a power plant system is made up of two identical, independent, and active units. At least one unit must work normally for its (i.e. system) success. Each unit can fail either due to a human error or due to a hardware failure. Constant human error and hardware failure rates of a unit are 0.0001 errors/h and 0.008 failures/h, respectively.

Calculate the power plant system mean time to failure.

By substituting the specified data values into Eq. (11.73), we obtain

$$\begin{aligned} \mathrm{MTTF}_{ps} &= \frac{3}{2(0.008 + 0.0001)} \\ &= 185.18\,\mathrm{h} \end{aligned}$$

Thus, the power plant system mean time to failure is 185.18 h.

11.8 Problems

1. Assume that a power plant operator's self-generated error correction times are Rayleigh distributed. Obtain an expression for the correctability probability function of the operator.

2. Prove Eqs. (11.12–11.14) using Eqs. (11.9–11.11) and the given initial conditions.
3. Assume that a power plant operator's constant non-critical and critical human error rates are 0.0006 and 0.0002 errors/h, respectively. Calculate the power plant operator's probability of making a non-critical human error during a 20-h mission.
4. Prove Eq. (11.35) using Eq. (11.34).
5. Prove that the sum of Eqs. (11.21), (11.26), (11.31), and (11.32) is equal to unity.
6. Prove Eqs. (11.47–11.49) using Eqs. (11.39), (11.44), and (11.45).
7. Prove Eq. (11.59) using Eq. (11.57).
8. Prove Eqs. (11.67–11.71) with the aid of Eqs. (11.62–11.66) and the given initial conditions.
9. Prove that the sum of Eqs. (11.67–11.71) is equal to unity.
10. A power plant system is composed of two identical, independent, and active units. At least one unit must operate normally for the system success. Each unit can fail either due to a hardware failure or due to a human error. Constant human error and hardware failure rates of a unit are 0.0003 errors/h and 0.009 failures/h, respectively.

Calculate the power plant system mean time to failure and reliability for a 150-h mission.

References

1. Dhillon BS (1986) Human reliability: with human factors. Pergamon Press Inc, New York
2. Regulinski TL, Askren WB (1972) Stochastic modelling of human performance effectiveness functions. In: Proceedings of the annual reliability and maintainability symposium, pp. 407–416
3. Dhillon BS (1985) Stochastic models for predicting human reliability. Microelectron Reliab 25:729–752
4. Dhillon BS (2003) Human reliability and error in medical system. World Scientific Publishing, River Edge
5. Dhillon BS (2007) Human reliability and error in transportation systems. Springer, London
6. Dhillon BS (2009) Human reliability, error, and human factors in engineering maintenance. CRC Press, Boca Raton
7. Askren WB, Regulinski TL (1969) Quantifying human performance for reliability analysis of systems. Hum Factors 11:393–396
8. Regulinski TL, Askren WB (1969) Mathematical modeling of human performance reliability. In: Proceedings of the annual symposium on reliability, pp. 5–11
9. Dhillon BS (1975) The analysis of the reliability of multi-state device networks. Ph.D. Dissertation, Available from the National Library of Canada, Ottawa, Canada
10. Dhillon BS (1999) Design reliability: fundamentals and applications. CRC Press, Boca Raton
11. Dhillon BS (2002) Engineering maintenance: a modern approach. CRC Press, Boca Raton

Author Biography

Dr. B.S. Dhillon is a professor of Engineering Management in the Department of Mechanical Engineering at the University of Ottawa. He has served as a Chairman/Director of Mechanical Engineering Department/Engineering Management Program for over 10 years at the same institution. He is the founder of the probability distribution named *Dhillon Distribution/Law/Model* by statistical researchers in their publications around the world. He has published over 369 (i.e., 222(70 *single authored* + 152 *co-authored*) journal and 147 conference proceedings) articles on reliability engineering, maintainability, safety, engineering management, etc. He is or has been on the editorial boards of 11 international scientific journals. In addition, Dr. Dhillon has written 41 books on various aspects of health care, engineering management, design, reliability, safety, and quality published by Wiley (1981), Van Nostrand (1982), Butterworth (1983), Marcel Dekker (1984), Pergamon (1986), etc. His books are being used in over 100 countries and many of them are translated into languages such as German, Russian, Chinese, and Persian (Iranian).

He has served as General Chairman of two international conferences on reliability and quality control held in Los Angeles and Paris in 1987. Prof. Dhillon has also served as a consultant to various organizations and bodies and has many years of experience in the industrial sector. At the University of Ottawa, he has been teaching reliability, quality, engineering management, design, and related areas for over 33 years and he has also lectured in over 50 countries, including keynote addresses at various international scientific conferences held in North America, Europe, Asia, and Africa. In March 2004, Dr. Dhillon was a distinguished speaker at the Conf./Workshop on Surgical Errors (sponsored by White House Health and Safety Committee and Pentagon), held at the Capitol Hill (One Constitution Avenue, Washington, D.C.).

Professor Dhillon attended the University of Wales where he received a BS in electrical and electronic engineering and an MS in mechanical engineering. He received a Ph.D. in industrial engineering from the University of Windsor.

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6,

Appendix
Bibliography: Literature on Human Reliability, Error, and Human Factors in Power Generation

A.1 Introduction

Over the years, a large number of publications on human reliability, error, and human factors in power generation have appeared in the form of journal articles, conference proceedings articles, technical reports, and so on. This appendix presents an extensive list of selective publications related, directly or indirectly, to human reliability, error, and human factors in power generation. The period covered by the listing is from 1971 to 2012. The main objective of this listing is to provide readers with sources for obtaining additional information on human reliability, error, and human factors in power generation.

A.2 Publications

1. Albert, T.P., et. al, A Computer-vision Based Power Flat Monitoring System, Proceedings of the IEE International Conference on Advances in Power System Control, Operation and Management, 1991, pp. 20–24.
2. Amendola, A., et. al, PSA Models for System and Human Reliability: Results on Benchmark Exercises and Needs, Maintenance Management International, Vol. 6, 1980, pp. 105–119.
3. Annick, C., An EDF Perspective on Human Factors, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1988, pp. 65–67.
4. Aslam, M.F., Lidgate, D., Shami, T.A., A Coupled Knowledge Based System for Online Economic Dispatch of Multiple Fuel Units in a Thermal Plant, Proceedings of the International Universities Power Engineering Conference, 2004, pp. 358–362.
5. Austin, R.C., 500 MW Unit Control Center—Operations and Maintenance Oriented, Instrumentation in Power Industry, Vol. 11, 1988, pp. 56–66.

B. S. Dhillon, *Human Reliability, Error, and Human Factors in Power Generation*, Springer Series in Reliability Engineering, DOI: 10.1007/978-3-319-04019-6,

6. Ayres, T.J., Gross, M.M., Exploring Power Plant Data Resources for Organizational Epidemiology, New Century, New Trends, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2002, pp. 10–16.
7. Azadeh, A., Jamshidnezhad, B, Improvement of Information Flow in a Thermal Power Plant within the Macro Ergonomics Framework, Proceedings of the SICE Annual Conference, 2005, pp. 59–64.
8. Azadeh, A., Fam, I.M., Garakani, M.M., A Total Ergonomic Design Approach to Enhance the Productivity in a Complicated Control System, Information Technology Journal, Vol. 6, No. 7, 2007, pp. 1036–1042.
9. Azadeh, A., Hasani, F.A., Jiryaei, S.Z, Performance Assessment and Optimization of HSE Management Systems with Human Error and Ambiguity by an Integrated Fuzzy Multivariate Approach in a Large Conventional Power Plant Manufacture, Journal of Loss Prevention in the Process Industries, Vol. 25, No. 3, 2012, pp. 594–603.
10. Azadeh, M.A., Keramati, A., Mohammadfam, I., Jamshidnedjad, B., Enhancing the Availability and Reliability of Power Plants through Macro Ergonomics Approach, Journal of Scientific and Industrial Research, Vol. 65, No. 11, 2006, pp. 873–878.
11. Bagchi, C.N., Gottilla, S.C., Application of Human Engineering Criteria to Annunciator Display Systems in a Large Fossil Power Station, IEEE Transactions on Power Apparatus and Systems, Vol. 100, No. 6, 1981, pp. 2759–2765.
12. Banks, W.W., Blackman, H. S., Curtis, J. N., A Human Factors Evaluation of Nuclear Power Plant Control Room Annunciators, Proceedings of Annual Control Engineering Conference, 1984, pp. 323–326.
13. Baur, P., Strategies For Eliminating Human Error in the Control Room, Power, Vol. 27, No. 5, 1983, pp. 21–29.
14. Beare, A.N., Gaddy, C.D, Gilmore, W.E, Taylor, J.C, Fray, R.R., Divakaruni, S.M., Human Factors Guidelines for Fossil Power Plant Digital Control System Displays, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1992, pp. 248–253.
15. Beattie, J.D., Bell, R.L., Ho, D.L.C., Howard, B., A Computer-Based CRT Display System for the Thunder Bay Generating Station Control Center, Proceedings of the Power Industry Computer Applications Conference, 1977, pp. 42–50.
16. Bedreage, L., Guzun, B.D., Constantinescu, C., Modelling of the Human Factors Using Petri Nets, Proceedings of the IREP Symposium on Bulb Power System Dynamics and Control, 2007, pp. 100–104.
17. Beltracchi, L., Iconic Displays, Ranking Cycles and Human Factors for Control Rooms of Nuclear Power Plants, IEEE Transactions on Nuclear Science, Vol. 30, 1983, pp. 1856–1861.
18. Ben-Yaacov, G., Human Factors Considerations in the Design of the Man–Machine Interface for Power Plant Process Computers, Proceedings of the Conference on Instrumentation in the Power Industry, 1980, pp. 19–33.

19. Bersini, U., Cacciabue, P.C., Mancini, G., Cognitive Modelling: A Basic Complement of Human Reliability Analysis, Reliability Engineering & System Safety, Vol. 22, 1988, pp.107–128.
20. Besco, R, Human Performance Breakdowns are Rarely Accidents: They are Unusually very Poor Choices with Disastrous Results, Journal of Hazardous Materials, Vol. 115, No. 1–3, 2004, pp. 155–161.
21. Beveridge, R.L., Applied Human Reliability: One Utility's Experience, Proceedings of the IEEE Conference on Human Factors and Nuclear Safety, 1985, pp. 316–320.
22. Bongarra, J.P., Certifying Advanced Plants: A US NRC Human Factors Perspective, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1997, pp. 6.18–6.24.
23. Boring, R.L., Blackman, Harold. S., The Origins of the SPAR-H Method's Performance Shaping Factor Multipliers, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp.177–184.
24. Boring, R.L., et. al, A Taxonomy and Database for Capturing Human Reliability and Human Performance Data, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2006, pp. 2217–2221.
25. Boring, R.L., et. al, Human Reliability Analysis in the U.S. Nuclear Power Industry: A Comparison of Atomistic and Holistic Methods, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2005, pp. 1814–1819.
26. Boring, R.L., et. al., Human Factors and the Nuclear Renaissance, Proceedings of the Human Factors and Ergonomics Society Conference, 2008, pp. 763–767.
27. Boring, R.L., Griffith, C.D., Joe, J.C., The Measure of Human Error : Direct and Indirect Performance Shaping Factors, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 170–176.
28. Boring, R.L., Human Reliability Analysis for Control Room Upgrades, Proceedings of the Human Factors and Ergonomics Society Conference, 2009, pp. 1584–1588.
29. Boring, R.L., Modeling Human Reliability Analysis Using MIDAS, Proceedings of the International Workshop on Future Control Station Designs and Human Performance Issues in Nuclear Power Plants, 2009, pp. 89–92.
30. Boring, R.L., Modeling Human Reliability Analysis Using MIDAS, Proceedings of the International Topical Meeting on Nuclear Plant Instrumentation Control, and Human Machine Interface Technology, 2006, pp. 1270–1274.
31. Boring, R.L., Using Nuclear Power Plant Training Simulators for Operator Performance and Human Reliability Research, Proceedings of the American Nuclear Society International Topical Meeting on Nuclear Power Plant Instrumentation Controls, and Human Machine Interface Technology, 2009, pp. 1–12.

32. Bransby, M., Human Contribution to Safety: Designing Alarm Systems for Reliable Operator Performance, Measurement and Control, Vol. 32, No.7, 1999, pp. 209–213.
33. Brown, R., Sanchez, J., Mudry, R., Fleming, M., Evaluation of Extractive Measurement Methods at the EPRI Coal Flow Loop, Proceedings of the Annual Joint ISA/EPRI Controls and Instrumentation Conference, 2006, pp. 346–349.
34. Byung-Soo, C., Chae-Joo, M., Design of Fuzzy Seawater Lift Pump System in Fossil Fired Power Plant, Proceedings of the Third International Symposium on Uncertainty Modeling and Analysis and Annual Conference of North American Fuzzy Information Processing Society, 1995, pp. 204–208.
35. Cacciabue, P.C., Evaluation of Human Factors and Man–Machine Problems in the Safety of Nuclear Power Plants, Nuclear Engineering and Design, Vol. 109, No. 3, 1988, pp. 417–431.
36. Carnino, A., Human Reliability, Nuclear Engineering and Design, Vol. 90, No. 3, 1985, pp. 365–369.
37. Carpignano, A., Piccini, M., Cognitive Theories and Engineering Approaches for Safety Assessment and Design of Automated Systems: A Case Study of Power Plant, Cognition Technology & Work, Vol. 11, No. 1, 1999, pp. 47–61.
38. Carvalho, P.V.R., et. al, Human Factors Approach for Evaluation and Redesign of Human-System Interfaces of a Nuclear Power Plant, Simulator, Displays, Vol. 29, 2008, pp. 273–284.
39. Cepin, M., Prosek, A., Update of the Human Reliability Analysis for a Nuclear Power Plant, Proceedings of the International Conference on Nuclear Energy for New Europe, 2006, pp. 706.1–706.8.
40. Choi, S.S., et. al, Development Strategies of an Intelligent Human–Machine Interface for Next Generation Nuclear Power Plants, IEEE Transactions on Nuclear Science, Vol. 43, No. 3, 1996, pp. 2096–2114.
41. Clarke, L.R ., Allamby, S.P., People in Power System Control in the Next Century, Proceedings of the International Conference on Human Interfaces in Control Room, Cockpits, and Command Centres, 1999, pp. 434–439.
42. Collins, E.P., Mcfadden, R.H., A Human Reliability Analysis Methodology for Industrial and Process Facilities, Proceedings of the IEEE Industrial and Commercial Power Systems Technical Conference, 1988, pp. 81–84.
43. Comer, K., Human Reliability Data Bank: Feasibility Study, Proceedings of the Human Factors Society Conference, 1984, pp. 235–238.
44. Comer, K., Miller, D.P., Donovan, M., Human Reliability Data Bank: Feasibility Study, Proceedings of the Human Factors Society Annual Meeting, 1984, pp. 235–238.
45. Comer, K., Miller, D.P., Human Reliability Data Bank: Pilot Implementation, Proceedings of the Human Factors and Ergonomics Society Conference, 1983, pp. 175–179.
46. Coury, B.G., Terranova, M., Collaborative Decision Making in Dynamic Systems, Proceedings of the Human Factors Society Annual Meeting, 1991, pp. 944–948.

47. Danchak, M.M., CRT Displays for Power Plants, Instrumentation Technology, Vol. 23, No. 10,1976, pp. 29–36.
48. Dang, V.N., et. al, An Empirical Study of HRA Methods—Overall Design and Issues, Proceedings the IEEE Conference on Human Factors and Power Plants, 2007, pp. 243–247.
49. Dang,V., Huang, Y., Siu, N., Carroll, J ., Analyzing Cognitive Errors using a Dynamic Crew-Simulation Model, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1992, pp. 520–526.
50. Daniel, T., Jean-Paul, L., The Impact on Safety of Computerized Control Room in Nuclear Power Plants: The French Experience on Human Factors with N4 Series, Proceedings of the IEA/HFES Congress, 2000, pp. 815–818.
51. Daniels, R.W., Formula for Improved Plant Maintainability Must Include Human Factors, Proceedings of the IEEE Conference on Human Factors and Nuclear Safety, 1985, pp. 242–244.
52. De, A., Thakur, S.S., Failure Analysis of Boiler in Thermal Power Station—A Study, Journal of the Institution of Engineers: Mechanical Engineering Division, Vol. 73, 1992, pp. 179–181.
53. Dicken, C.R., Soft Control Desks and Alarm Display, Computer & Control Engineering Journal, Vol. 10, No. 1, 1999, pp. 11–16.
54. Dicken, C.R., Soft Control Desks—the Operator Interface, Proceedings of the UKACC International Conference on Control, 1998, pp. 567–571.
55. Dineen,G.J., Development and Implementation of an Enhanced Maintenance System for a 30 year old Power Station, Proceedings of First IEE International Conference on Power Station Maintenance, 1988, pp. 6–10.
56. Dougherty, E.M., Fragola, J.R., Foundations for a Time Reliability Correlation System to Quantify Human Reliability, IEEE Conference on Human Factors and Power Plants, 1998, pp. 268–278.
57. Downes, B., Sandar, D., Human Reliability Program—Components and Effects, Nuclear Materials Management, Vol. 15, 1986, pp. 661–665.
58. Doytchev, D., Szwillus, G., Combining Task Analysis and Fault Tree Analysis for Accident and Incident Analysis: A Case Study from Bulgaria, Proceedings of the European Safety and Reliability Conference, 2006, pp. 3–10.
59. Doytchev, D.E., Combining Task Analysis and Fault Tree Analysis for Accident and Incident Analysis: A Case Study from Bulgaria, Accident Analysis and Prevention, Vol. 41, No. 6, 2009, pp. 1172–1179.
60. Duffey, R.B., Saull, J.W., The Probability and Management of Human Error, Proceedings of the International Conference on Nuclear Energy, 2004, pp. 133–137.
61. Esther, D.S., Heising, C.D., Impact of the Organization on Human Reliability at Ft. Calhoun Nuclear Plant, Transactions of the American Nuclear Society, Vol. 88, 2003, pp. 888–889.
62. Etemadi, A.H., Fotuhi-Firuzabad, M., Quantitative Assessment of Protection System Reliability Incorporating Human Errors, Journal of Risk and Reliability, Vol. 9, 2008, pp. 255–263.

63. Farinha, T., Fonseca, I ., Simoes, A., Barbosa, M., Viejas, J., New Approaches on Predictive Maintenance Based on an Environmental Perspective, the Cases of Wind Generators and Diesel Engines, Proceedings of the 12th WSEAS International Conference on Circuits, 2008, pp. 420–428.
64. Fenton, E.F., et. al, Development of a Unit Control System Concept for Lakeview Generating Station, Proceedings of Instrumentation,Control,and Automation in the Power Industry, Vol. 33,1990, pp. 245–250.
65. Fiedlander, M.A., Evans, S.A., Influence of Organizational Culture on Human Error, Global Perspective of Human factors in Power Generation, Proceedings of the IEEE Conference on Human Factors and Power Plants,1997, pp. 19–22.
66. Fink, B., Hill, D., Nasser, J., Planning for Control Room Modernization, Proceedings of the American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human Machine Interface Technology, 2004, pp. 1475–1483.
67. Fledger, S. A., McWilliams, M. R., Control Room Human Factors Assessment at Bulgarian Power Plants, Proceedings of the Human Factors and Ergonomics Society Meeting, 1995, pp. 1043–1047.
68. Floyd II, H.L, Industrial Electric Power System Operation, Part I—Improving System Reliability, Proceedings of the IEEE Industrial and Commercial Power Systems Technical Conference, 1984, pp. 153–158.
69. Floyd II, H.L., Reducing Human Errors in Industrial Electric Power System Operation, Part I—Improving System Reliability, IEEE Transactions on Industry Applications, Vol. 22, No. 3, 1986, pp. 420–424.
70. Forzano, P., Castagna, P., Procedures, Quality, Standards, and the Role of Human Factors and Computerized Tools in Power Plant Control, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1997, pp.7–12.
71. Fredricks, P., Humanizing the Power Plant Control Room, Instrumentation in the Power Industry, Vol. 23, 1980, pp. 149–153.
72. Fuchs, S., Hale, K.S., Axelsson, P, Augmented Cognition Can Increase Human Performance in the Control Room, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 128–132.
73. Gaddy, C.D., Taylor, J.C., Fray, R. R., Divakaruni, S. M., Human Factors Considerations in Digital Control Room Upgrades, Proceedings of the American Power Conference, 1991, pp. 256–258.
74. Gong-Xia, Y., Gen-Xing, C., Jue-Zhong, J., A Case Study for the Design of Visual Environment of a Control Room in a Power Plant, Lighting Research and Technology, Vol. 17, No. 2, 1985, pp. 84–88.
75. Groth, K., Mosleh, A., Data-Driven Modelling of Dependencies Among Influencing Factors in Human–Machine Interactions, Proceedings of the ANS/PSA Topical Meeting on Challenges to PSA During the Nuclear Renaissance, 2008, pp. 916–926.
76. Guttmann, H.E., Human Reliability Data: The Problem and Some Approaches, Transactions of the American Nuclear Society, Vol. 41, No. 1, 1982, pp. 1–25.

77. Ha, J.S., Seong, P.H., Lee, M.S., Hong, J. H., Development of Human Performance Measures for Human Factors Validation in the Advanced MCR of APR-1400, IEEE Transactions on Nuclear Science,Vol. 54, No. 6, 2007, pp. 2687–2699.
78. Hagen, E.W., Technical Note: Quantification of Human Error Associated with Instrumentation and Control System Components, Nuclear Safety, Vol. 23, No. 6, 1982, pp. 665–668.
79. Hallbert, B.P., The Evaluation of Human Reliability in Process Systems Analysis, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1992, pp. 442–447.
80. Hannaman, G.W., The Role of Framework, Models, Data, and Judgement in Human Reliability, Nuclear Engineering and Design, Vol. 93, 1986, pp. 295–301.
81. Harper, A.B, Nicholas, G.R, Retrofit of Instrumentation and Controls for Large Industrial and Utility Power Plants, Proceedings of the Conference on Trends in the Generation, Transmission, Distribution and Utilisation of Electrical Energy, 1985, pp. 273–276.
82. Harrison, M., Barnard, P., On Defining Requirements for Interaction, Proceedings of the IEEE International Symposium on Requirements Engineering, 1992, pp. 50–54.
83. Heo, G., Framework of Quantifying Human Error Effects in Testing and Maintenance, Proceedings of the American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human–Machine Interface Technology, 2009, pp. 2083–2092.
84. Heo, G., Park, J., A Framework for Evaluating the Effects of Maintenance Related Human Errors in Nuclear Power Plants, Reliability Engineering and System Safety, Vol. 95, No. 7, 2010, pp. 797–805.
85. Heuertz, S.W., Herrin, J.L., Validation of Existing Nuclear Station Instrumentation and Electric Procedures to Reduce Human Errors: One Utility's Perspective, IEEE Transactions on Energy Conversions, Vol. 1, No. 4, 1986, pp. 33–34.
86. Higginbotham, J.W., Implementation of Human Factors Consideration in a Coal Generating Station Control Room, IEEE Transactions on Power Apparatus and Systems, Vol. 104, No. 4, 1985, pp. 817–820.
87. Hill, D., et. al, Integration of Human Factors Engineering into the Design Change Process, Proceedings of the American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control, and Human–Machine Interface Technology, 2004, pp. 1485–1494.
88. Hoag, L.L., An Overview of Research Needs in the Display Systems Design Area, Proceedings of the Human Factors Society Annual Meeting, 1977, pp.316–318.
89. Holmberg, K, New Techniques for Competitive Reliability, International Journal of Comadem, Vol. 4, No. 4, 2001, pp. 41–46.

90. Hopkins, C.O., Synder, H.L., Critical Human Factors Issue in Nuclear Power Generation and a Recommended Comprehensive Long Range Plan, Proceedings of the Human Factors Society Annual Meeting, 1982, pp. 692–697.
91. Howey, G.R., Human Factors in Ontario Hydro's Nuclear Power Stations, IEEE Transactions on Nuclear Science, Vol. 28, No. 1, 1981, pp. 968–971.
92. Hunt, R.M., Rouse, W.B., Problem-Solving Skills of Maintenance Trainees in Diagnosing Faults in Stimulating Power Plants, Human factors, Vol. 23, No. 3, 1981, pp. 317–328.
93. Hvelplund, R., Control Room for High-Efficiency Power Plant, People in Control, Proceedings of the International Conference on Human Interfaces in Control Room, Cockpits and Command Centres, 1999, pp. 101–117.
94. Jankala, K.E., Vaurio, J.K., Vuorio, U.M., Plant-specific Reliability and Human Data Analysis for Safety Assessment, Proceedings of the IAEA Conference on Nuclear Power Performance and Safety, 1988, pp. 135–151.
95. Johnson, W.B., Rouse, W.B., Analysis and Classification of Human Errors in Troubleshooting Live Aircraft Power Plants, IEEE Transactions on Systems, Man and Cybernetics, Vol. 12, No. 3, 1982, pp. 389–393.
96. Jones, J., Human Factors in the Acquisition of Data, Control & Instrumentation, Vol. 22, No. 12, 1990, pp. 31–32.
97. Joseph, L., Human Factors Assessment of Digital Monitoring Systems for Nuclear Power Plants Control Room, IEEE Transactions on Nuclear Science, Vol. 39, No. 4, 1992, pp. 924–932.
98. Jou, Y.T., et. al, The Implementation of a Human Factors Engineering Checklist for Human-System Interfaces Upgrade in Nuclear Power Plants, Safety Science, Vol. 47, No. 7, 2009, pp. 1016–1025.
99. Jufang, S., Human Errors in Nuclear Power Plants, Nuclear Power Engineering, Vol. 14, No. 4, 1993, pp. 306–309.
100. Jung, W., et. al, Analysis of an Operator's Performance Time and Its Application to a Human Reliability Analysis in Nuclear Power Plants, IEEE Transactions on Nuclear Science, Vol. 54, No. 4, 2007, pp. 1801–1811.
101. Jung, W., Park, J., Jaewhan, K., Performance Time Evaluation for Human Reliability Analysis Using a Full-Scope Simulator of Nuclear Power Plants, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2002, pp. 306–311.
102. Kang, D., Jung, W.D., Yang, J.E., Improving the PSA Quality in the Human Reliability Analysis of Pre-Accident Human Errors, Proceedings of the Annual Conference of the Canadian Nuclear Society, 2004, pp. 189–200.
103. Kawai, K., Takishima, S., Tsuchiya, M., Uchida, M., Operator Friendly Man–Machine System for Computerized Power Plant Automation, Bridge Between Control Science and Technology, Proceedings of the Ninth Triennial World Congress of IFAC (International Federation of Automatic Control), Vol. 5, 1985, pp. 2641–2646.

104. Kengskool, K., Martinez, S.E., Cobaugh, P, Robot vs. Human Operator for Speed, Precision and Other Aspects, Proceedings of the first International Conference on Ergonomics of Advanced Manufacturing and Hybrid Automated Systems, 1988, pp. 373–380.
105. Kenny, S.D., Stamps, K., Crowther, P., Development of NDT Techniques and Inspection for Detection and Sizing of Thermal Fatigue Cracking in Steam-Pipework Bores of Flexibly Operated Coal-Fired Power Stations, Insight-Non-Destructive Testing and Condition Monitoring, Vol. 45, No. 2, 2003, pp. 125–129.
106. Khalaquzzaman, M., et. al, A Model for Estimation of Reactor Spurious Shutdown Rate Considering Maintenance Human Errors in Reactor Protection System of Nuclear Power Plants, Nuclear Engineering and Design, Vol. 240, No. 10, 2010, pp. 2963–2971.
107. Khalaquzzaman, M., et. al, Quantification of Unavailability Caused by Random Failures and Maintenance Human Errors in Nuclear Power Plants, Nuclear Engineering and Design, Vol. 240, No. 6, 2010, pp. 1606–1613.
108. Kim, B.J., Bishu, R.R., Uncertainty of Human Error and Fuzzy Approach to Human Reliability Analysis, International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems, Vol. 14, No. 1, 2006, pp. 111–129.
109. Kim, I.S., Human Reliability Analysis in the Man–Machine Interface Design Review, Annals of Nuclear Energy, Vol. 29, No. 11, 2001, pp. 1069–1081.
110. Kim, J., et. al, Characteristics of Test and Maintenance Human Errors Leading to Unplanned Reactor Trips in Nuclear Power Plants, Nuclear Engineering and Design, Vol. 239, 2009, pp. 2530–2536.
111. Kim, J., Jung, W., Park, J., AGAPE-ET: Advanced Guidelines for Human Reliability Analysis of Emergency Tasks, Proceedings of the IEEE conference on Human Factors and Power Plants, 2007, pp. 314–321.
112. Kim, J.W., Jung, W., A Taxonomy of Performance Influencing Factors for Human Reliability Analysis of Emergency Tasks, Journal of Loss Prevention in the Process Industries, Vol. 16, No. 6, 2003, pp. 479–495.
113. Kirwan, B., Scannali, S., Robinson, L., A Case Study of a Human Reliability Assessment for an Existing Nuclear Power Plant, Applied Ergonomics, Vol. 27, No. 5, 1996, pp. 289–302.
114. Kirwan, D.O., Basra, G., Taylor-Adams, S.E., CORE-DATA: A Computerized Human Error Database for Human Reliability Support, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1997, pp. 7–9.
115. Knee, H.E., Human Factors Engineering: A Key Element of Instrumentation and Control System Design, Proceedings of the International Symposium on Instrumentation in the Aerospace Industry, 1993, pp. 1113–1122.
116. Knee, H.E., The Maintenance Personnel Performance Simulation (MAPPS) Model: A Human Reliability Analysis Tool, Proceedings of the International Conference on Nuclear Power Plant Aging, Availability Factor and Reliability Analysis, 1985, pp. 77–80.

117. Koehler, T.A., Schmachtenberger, C.L., Soft Approach to Innovative Control Room Design, Instrumentation in the Power Industry, Vol. 28, 1985, pp. 145–158.
118. Konig, N., Wetzl, R., Intelligent Instrumentation and Control Systems for Optimum Power Plant Operation, Engineering & Automation, Vol. 14, No. 6,1992, pp. 18–19.
119. Koval, D.O., Floyd, II, H.L., Human Element Factors Affecting Reliability and Safety, IEEE Transactions on Industry Applications, Vol. 34, No. 2, 1998, pp. 45–54.
120. Koval., D.O., Floyd II, H.L., Human Element Factors Affecting Reliability and Safety, Proceedings of the IEEE Industry and Commercial Power Systems Technical Conference, 1997, pp. 14–21.
121. Kozinsky, E.J., Computerized Measurement of Operator Performance on Simulators, Proceedings of the Winter Simulation Conference, 1981, pp. 10–14.
122. Lahiri, R.N., Sinha, A., A Web-Based Fuel Management Software System for a Typical Indian Coal Based Power Plant, Proceedings of the IEEE Power Engineering Society General Meeting, 2007, pp. 8–9.
123. Lang, A.W., Roth, E.M ., Bladh, K., Hine, R, Using a Benchmark—Referenced Approach for Validating a Power Plant Control Room: Results of the Baseline Study, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 2002, pp. 1878–1882.
124. Laux, l., Plott, C., Using Operator Workload Data to Inform Human Reliability Analyses, Proceedings the IEEE Conference on Human Factors and Power Plants, 2007, pp. 309–313.
125. LeBot, P., Human Reliability Data, Human Error and Accident Models: Illustration Through the Three Mile Island Analysis, Reliability Engineering and System Safety, Vol. 83, No. 2, 2004, pp. 153–167.
126. Lee, B., The Nuclear Power Industry's Approach to Human Factors, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1992, pp. 7–9.
127. Lee, J.W., et. al, Human Factors Research in KAERI for Nuclear Power Plants, Proceedings of the IEEE Annual Human Factors Meeting, 1997, pp. 13.11–13.16.
128. Lee, J.W., et. al., Human Factors Review Guide for Korean Next Generation Reactors, Proceedings of the 15th International Conference on Structural Mechanics in Reactor Technology, 1999, pp. 353–360.
129. Li, D., Li, L., Preliminary Study of Human Factor Reliability in Hydropower Station, Advanced Materials Research, Vol. 422, 2012, pp. 803–806.
130. Li, X., Human Reliability Analysis for Guangdong Nuclear Power Station, Atomic Energy Science and Technology, Vol. 27, No. 4, 1993, pp. 324–328.
131. Li, Z., Chao, H., Human Factors Analysis and Preventive Countermeasures in Maintenance in Nuclear Power Plants, Nuclear Power Engineering, Vol. 19, No. 1, 1998, pp. 64–67.

132. Lisboa, J.J., Nuclear Power Plant Availability and the Role of Human Factors Performance, IEEE Transactions on Nuclear Science, Vol. 37, No. 1, 1990, pp. 980–986.
133. Lisboa, J.J., Quantification of Human Error and Common-Mode Failures in Man–Machine Systems, IEEE Transactions on Energy Conversion, Vol. 3, No. 2, 1986, pp. 291–299.
134. Lois, E., Chang, Y., Hsien, J., Capturing Control Room Simulator Data with the HERA System, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 210–217.
135. Lois, E., Cooper, S.E., How Do You Define a Human Reliability Analysis Expert?, Invited, Transactions of the American Nuclear Society, Vol. 101, 2009, pp. 980–981.
136. Lubini, E.., Light from the Heart of Darkness, IET Power Engineer, Vol. 20, No. 4, 2006, pp. 42–45.
137. Ma, C., Lian, J., Long-Term Risk Dispatching of Cascaded Hydropower Stations in Electricity Market, Proceedings of the Asia–Pacific Power and Energy Engineering Conference, 2009, pp. 100–104.
138. Makansi, J., AES Extracts Top Performance from Diverse Asset Base, Power Engineering, Vol. 108, No. 11, 2004, pp.216–222 .
139. Manicut, M., Manicut, I., Human Reliability Analysis-Component of Probabilistic Safety Assessment of Nuclear Power Plant, Proceedings of the International Symposium on Nuclear Energy, 1993, pp. 207–211.
140. Manrique, A., Valdivia, J.C., Human Factors Engineering Applied to Nuclear Power Plant Design, Proceedings of the International Congress on Advances in Nuclear Power Plants, 2008, pp. 339–346.
141. Marshall, E.J., Dykes, J.E., Reduction in Plant Operating Costs Through Computer Evaluation of Operator Performance, Proceedings of the American Power Conference, 1984, pp. 380–384.
142. Mashio, K., Human Factors Engineering and HSI Design in the US-APWR, Proceedings of the Annual Joint ISA POWID/EPRI Controls and Instrumentation Conference, 2008, pp. 206–227.
143. Maskansi, J, Power Plant Training Ensure Your Team's Survival in the Trenches, Power, Vol. 139, No. 1, 1995, pp. 5–6.
144. McKeithan, B.G., Kfoury, N.S., Increasing Electric Power Plant Productivity through Maintenance Management, Proceedings of the Human Factors Society Annual Meeting, Vol. 1, 1983, pp. 576–580.
145. McWilliams, T.P., Martz, H.F., Human Error Considerations in Determining the Optimum Test Interval for Periodically Inspected Standby Systems, IEEE Transactions on Reliability, Vol. 29, No. 4, 1980, pp. 305–310.
146. Meshakti. N., The Safety and Reliability of Complex Energy Processing Systems, Energy Sources, Vol. 2, No. 2, 2007, pp. 141–154.
147. Meshkati, N, Control Rooms' Design in Industrial Facilities, Human Factors and Ergonomics in Manufacturing, Vol. 13, No .4, 1993, pp. 269–277.
148. Minner, D.E., The Inel Human Reliability Program: The First Two Years of Experience, Nuclear Materials Management, Vol. 15, 1986, pp. 666–669.

149. Mirabdolbaqi, S., The Role of the Operator in Power Plant Incidents: People in Control, Proceeding of the International Conference on Human Interfaces in Control Room, Cockpits and Command Centres, 1999, pp. 276–279.
150. Mishima, S., Human Factors Research Program-Long Term Plan in Cooperation with Government and Private Research Centers, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1988, pp. 50–54.
151. Miyazaki, T., Development of a New Cause Classification Method Considering Plant Aging and Human Errors for Adverse Events Occurred in Nuclear Power Plants and Some Results of Its Application, Transactions of the Atomic Energy Society of Japan, Vol. 6, No. 4, 2007, pp. 434–443.
152. Moieni, P., Spurgin, A.J., Singh, A., Advances in Human Reliability Analysis Methodology, Reliability Engineering and System Safety, Vol. 44, No. 1, 1994, pp. 27–55.
153. Mookerjee, G., Mandal, J, Modern Control Center Design—The Influence of Operator Interface on Control Room Instrumentation and Control Devices, Considering the Philosophy of Human-Factor Engineering Principles, Proceedings of the American Power Conference, 1998, pp. 1009–1014.
154. Mookerjee, G., Modern Control Center Design—the Influence of Operator Interface on Control Room Instrumentation and Control Devices, Considering the Philosophy of Human-Factors Engineering Principles, Proceedings of the American Power Conference on Reliability and Economy, 1998, pp. 1009–1014.
155. Morgenstern, M.H., Maintenance Management Systems: A Human Factors Issue, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1988, pp. 390–393.
156. Moshely, A., Chang, Y.H., Model-Based Human Reliability Analysis: Prospects and Requirements, Reliability Engineering and System Safety, Vol. 83, No. 2, 2004, pp. 241–253.
157. Mosneron-Dupin, F., Saliou, G., Lars, R., Probabilistic Human Reliability Analysis: The Lessons Derived for Plant Operation at Electric de France, Reliability Engineering and System Safety, Vol. 58, No. 3, 1997, pp. 249–274.
158. Mulle, G.R., Dick, R., The Role of Human Factors in Planning for Nuclear Power Plant Decommissioning, Proceedings of the IEEE Conference on Human Factors and Nuclear Safety, 1985, pp. 257–262.
159. Muschara, T., A Dual Human Performance Strategy: Error Management and Defense-in-Depth, Proceedings of the IEEE Human Factors Meeting, 2002, pp.830–839.
160. Naser, J., Addressing Digital Control Room Human Factors Technical and Regulatory Issues, Proceedings of the American Nuclear Society International Meeting on Nuclear Plant Instrumentation, control and Human–Machine Interface Technology, 2009, pp. 6–10.
161. Naser, J., et. al, Nuclear Power Plant Control Room Modernization Planning, Process, Human Factors Engineering, and Licensing Guidance, Proceedings of the Annual Joint ISA Power Industry Division and EPRI Controls and Instrumentation Conference, 2004, pp. 219–227.

162. Naumov, V.I., Human Factors and Supporting Measures for Nuclear Power Plant Operators, Atomnaya Energiya, Vol. 74, No. 4, 1993, pp. 344–348.
163. Nelson, R., Dynamic Accident Sequence Analysis in PRA: A Comment on "Human Reliability Analysis-Where Shouldst Thou Turn?", Reliability Engineering and System Safety, Vol. 29, 1990, pp. 359–364.
164. Nelson, W.R., Integrated Design Environment for Human Performance and Human Reliability Analysis, Proceedings of the IEEE conference on Human Factors and Power Plants, 1997, pp. 8.7–8.11.
165. Nimmo, I., Moscatelli, J., Designing Control Rooms for Humans, Control, Vol. 17, No. 7, 2000, pp. 47–53.
166. Nimmo, L., Putting a Human Face on the Design of Control Rooms, Engineering Technology, Vol. 7, No. 4, 2004, pp. 42–44.
167. Nitu. V.l, Lonescu, D.C., Binig.V., Barrakat, M.T., Human Reliability: Revue Roumaine des Sciences Techniques, Serie Electrotechnique et Energetique, Vol. 35, No. 2, 1990, pp. 179–185.
168. O' Brien, J.N., Lukas, W.J., A Strategy for Examining Human Reliability Aspects of Plant Security, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1998, pp. 465–470.
169. O'Hara, J.M., A Quasi-Experimental Model of Complex Human–Machine System Validation, Cognition, Technology & Work, Vol. 1, No. 1, 1999, pp. 37–46 .
170. O'Hara, J.M., Brown, W.S., Higgins, J.C., Updating the NRC's Guidance for Human Factors Engineering Reviews, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2002, pp. 422–427.
171. O'Hara, J.M., Hall, R.E., Advanced Control Rooms and Crew Performance Issues: Implications for Human Reliability, IEEE Transactions on Nuclear Science, Vol. 39, No. 4, 1992, pp. 919–923.
172. Obrzut, J.J., Good Plant Design Cuts Human Errors, Iron Age, Vol. 27, No. 16, 1971, pp. 78–79.
173. Orendi, R.G., et. al, Human Factors Consideration in Emergency Procedure Implementation, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1988, pp. 214–221.
174. Oxstarnd, J., Boring, R.L., Human Reliability for Design Applications at a Swedish Nuclear Power Plant, Proceedings of the International Symposium on Resilient Control Systems, 2009, pp. 5–10.
175. Pack, R.W., Parris, H.L., Human Factors Engineering Design Guidelines for Maintainability, Proceedings of the Inter-RAM Conference for the Electric Power Industry, 1985, pp. 11–14.
176. Paradies, M., Positive vs. Negative Enforcement: Which Promotes High Reliability Human Performance, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 185–188.
177. Paradies, M., Skompski, E., Why People Don't Develop Effective Corrective Actions, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2002, pp. 18–22.

178. Parsons, S.O., Saminara, J.L., O'Hara, J.M., Power System Human Factors/Ergonomics Activities in United States, Proceedings of the XIV Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of Human Factors and Ergonomic Association, 2000, pp. 807–810.
179. Penington, J., Shakeri, S., A Human Factors Approach to Effective Maintenance, Proceedings of the Canadian Nuclear Society Conference, 2006, pp. 1–11.
180. Pesme, H., Le Bot, P., Meyer, P., Little Stories to Explain Human Reliability Assessment: A Practical Approach of MERMOS method, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 284–287.
181. Piccini, M, Human Factors in the Design of Supervisory Control Systems and Human–Machine Interfaces for Highly Automated Complex Systems, Cognition, Technology & Work, Vol. 4, No. 4, 2002, pp. 256–71.
182. Pine, S.M., Schulz, K.A., Applying Human Engineering Processes to Control Room Design, Power Engineering Vol. 87, No.1,1983, pp. 38–46.
183. Poucet, A., Survey of Methods Used to Assess Human Reliability in the Human Factors Reliability Benchmark Exercise, Reliability Engineering and System Safety, Vol. 22, 1988, pp. 257–268.
184. Presensky, J.J., Human Factors and Power Plants: Foreword, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2002, pp. 3–4.
185. Prevost, M., et. al., Preventing Human Errors in Power Grid Management Systems Through User Interface Design, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 2007, pp. 626–631.
186. Pyy, P., Laakso, K., Reiman, L., Study of Human Error Related to NPP Maintenance Activities, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1997, pp. 12.23–12.28.
187. Pyy. P., An Approach for Assessing Human Decision Reliability, Reliability Engineering and System Safety, Vol. 68, No. 1, 2000, pp. 17–28.
188. Reiman, T., Oedewald, P., Organizational Factors and Safe Human Performance Work Physiological Model, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 140–144.
189. Rinkus, E.K., Power-Unit Control: Will Automation Replace the Operator, Thermal Engineering, Vol. 42, No. 3, 1995, pp. 256–258.
190. Rja, P., Miller, C.A., Trust and Etiquette in High-Criticality Automated Systems, Communications of the ACM, Vol. 47, No. 4, 2004, pp. 51–55.
191. Ryan, T.G., A Task Analysis-Linked Approach for Integrating the Human Factor in Reliability Assessments of Nuclear Power Plants, Reliability Engineering and System Safety, Vol. 22, No. 14, 1987, pp. 219–234.
192. Salge, M, Milling, P.M., Who is to Blame, the Operator or the Designer? Two Stages of Human Failure in the Chernobyl Accident, System Dynamics Review, Vol. 22, No. 2, 2006, pp. 89–112.
193. Schroeder, L.R., Gaddy, C.D., Beare, A. N., New Control Technologies Require Good Human Factors Engineering, Power Engineering, Vol. 93, No. 11, 1989, pp. 29–32.

194. Seminara, J.L., Parsons, S.O., Human Factors Engineering and Power Plant Maintenance, Maintenance Management International, Vol. 6, No. 1, 1980, pp. 33–71.
195. Seminara, J.L., Parsons, S.O., Survey of Control-Room Design Practices with Respect to Human Factors Engineering, Nuclear Safety, Vol. 21, No. 5, 1980, pp. 603–617.
196. Skof, M., Molan, G., Impacts of Human Fitness for Duty on System's Performance—Human Reliability and System's Performance, Proceedings of the International Conference on PSA/PRA and Severe Accidents, 1994, pp. 428–435.
197. Smith, D.J., Integrated Control Systems: The Next Step, Power Engineering, Vol. 95, No. 9, 1991, pp. 17–21.
198. Smith, L., Human Factors: Operator Task Analysis, ASME Safety Engineering and Risk Analysis, Vol. 1, 1994, pp. 57–61.
199. So, A.T.P., Chan,W.L., A Computer-Version Based Power Plant Monitoring System, Proceedings of the International Conference on Advances in Power System Control, Operation, and Management, 1991, pp. 335–340.
200. Sola, R., Nunez, J., Torralba, B., An Overview of Human Factors Activities in CIEMAT, Proceedings of the IEEE Annual Human Factors Meeting, 1997, pp. 131–134.
201. Spurgin, A., Another View to the State of Human Reliability Analysis, Reliability Engineering and System Safety, Vol. 29, No. 3, 1990, pp. 365–370.
202. Spurgin, A.J., Human/System Reliability in a Changing Environment, Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, 2004, pp. 2746–2751.
203. Spurgin, A.J., Lydell, B.O.Y., Critique of Current Human Reliability Analysis Methods, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2002, pp. 312–318.
204. Staples, L., McRobbie, H., Design Changes and Human Factors, Nuclear Plant Journal, Vol. 2, No. 1, 2004, pp. 41–45.
205. Sternheim, E., Moser, T.D., System Design Considerations for High Powered Testing with Real Time Computers, Proceedings of the Power Industry Computer Applications Conference, 1977, pp. 407–410.
206. Stojka, T., Use of Expert Judgements for Assessment of Performance Shaping Factors in Human Reliability Analysis, Proceedings of the American Nuclear Society International Topical Meeting on Probabilistic Safety Analysis, 2005, pp. 619–623.
207. Strater, O., Bubb, H., Assessment of Human Reliability Based on Evaluation of Plant Experience: Requirements and Implementation, Reliability Engineering and System Safety, Vol. 63, No. 2, 1999, pp. 199–219.
208. Strater, O., Consideration on the Elements of Quantifying Human Reliability, Reliability Engineering and System Safety, Vol. 83, No. 2, 2004, pp. 255–264.

209. Strod, A.A., The Importance of Human Factors in Performing Maintenance Tasks Inside the Containment of a Nuclear Power Plant, Proceedings of the Annual Engineering Conference on Reliability for the Electric Power Industry, 1980, pp. 82–87.
210. Stultz, S.W., Schroeder, L.R., Incorporating Human Engineering Principles in Distributed Controls Upgrades, Instrumentation, Control, and Automation in the Power Industry, Vol. 31, 1988, pp. 135–141.
211. Sundstorm, G.A., User Modelling: A New Technique to Support Designers of Graphical Support Systems in Conventional Power Plants, Proceedings of the International Federation of Automatic Control Conference, 1989, pp. 53–57.
212. Swain, A.D., Gutmann, H.E., Human Reliability Analysis Applied to Nuclear Power, Proceedings of the Annual Reliability and Maintainability Symposium, 1975, pp. 116–119.
213. Swaton, E., Neboyan, V., Lederman, L., Human Factors in the Operation of Nuclear Power Plants, International Atomic Energy Bulletin, Vol. 29, No. 4, 1987, pp. 27–30.
214. Sword, J, How Do You Know What You Don't know? Detecting "Hidden Trends" in Performance, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 38–41.
215. Takehisa, O., An Approach to Human Reliability in Man Machine Systems Using Errors Possibility, Fuzzy Sets and Systems, Vol. 27, 1988, pp. 87–103.
216. Tennant, D.V., Human Factors Consideration in Power Plant Design, Instrumentation in Power Industry, Vol. 29, 1986, pp. 29–36.
217. Thunberg, A., What Constitutes a Well-Designed Alarm System?, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 85–91.
218. Tonkinson, Tyrone S., SAI's Behaviour-Based Root Cause Analysis, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 288–290.
219. Trager, E.A., Human Errors in Events Involving Wrong Unit or Wrong Train, Nuclear Safety, Vol. 25, No. 5, 1983, pp. 697–703.
220. Tran, T.Q., Boring, R.L., Joe, J.C., Griffith, C.D., Extracting and Converting Quantitative Data into Human Error Probabilities, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 164–169.
221. Trubitsyn, V.I., Solov'ev, A.I., Consideration of Operator Activity in Evaluation of Thermal Power Station Unit Performance Reliability, Applied Energy: Russian Journal of Fuel, Power and Heat Systems, Vol. 31, No. 4, 1993, pp. 95–103.
222. Usher, D.M., Experience with Touch-Screens, IEE Colloquium on Developments in the Man–Machine Interface in Power Stations, Vol. 6, 1986, pp. 1–4.
223. Usher, D.M., Llett, C., Touch-Screen Techniques: Performance and Application in Power Station Control Displays, Displays, Vol. 7, No. 2, 1986, pp. 56–66.

224. Van Cott, H.P., The Application of Human Factors by Doe Nuclear Facilities, Proceedings of the Human Factors Society Annual Meeting, 1984, pp. 138–139.
225. Varma,V., Maintenance Training Reduces Human Errors, Power Engineering, Vol. 100, No. 8, 1996, pp. 44–47.
226. Varnicar, J.J., Use of Mockups for Control Panel Enhancements, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1985, pp. 41–44.
227. Vaurio, J.K., Human Factors, Human Reliability and Risk Assessment in Licence Renewal of a Nuclear Power Plant, Reliability Engineering and System Safety, Vol. 94, No. 11, 2009, pp. 1818–1826.
228. Voss, T.J., An Overview of IEEE Human Factors Standard Activities, Proceedings of the American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Control and Human Machine Interface Technology, 2004, pp. 875–880.
229. Wei, L., He, X.H., Zhao, B.Q., Research on the Relationship Between Nuclear Power Plant Operator's Reliability and Human Quality, Atomic Energy Science and Technology, Vol. 38, No. 4, 2004, pp. 312–316.
230. Wenhui, Z., Validation of Control System Specifications with Abstract Plant Models, Proceedings of the International Conference on Computer Safety, Reliability and Security, 2000, pp. 53–62.
231. Whaley, A.M., Boring, R.L., Blackman, H.S., McCabe, P.H., Hallbert, B.P, Lessons Learned From Dependency Usage in HERA: Implications for THERP-Related HRA Methods, Proceedings of the IEEE Conference on Human Factors and Power Plants, 2007, pp. 322–327.
232. Widrig, R.D., Human Factors: A Major Issue in Plant Aging, Proceedings of the International Conference on Nuclear Power Plant Aging, Availability Factor, and Reliability Analysis, 1985, pp. 65–68.
233. Wiegmann, D. A., Overbye, T. J., Human Factors Aspects of Three-Dimensional Visualization of Power System Information, Proceedings of the IEEE Power Engineering Society General Meeting, 2006, pp. 1–7.
234. Williams, A.R., Jr, Seidenstein. S., Goddard, C.J, Human Factors Survey and Analysis of Electric Power Control Centers, Proceedings of the Human factors Society Annual Meeting, 1980, pp. 276–279.
235. Williams, J.C., A Data Based Method for Assessing and Reducing Human Error to Improve Operational Performance, Proceedings of the IEEE Conference on Human Factors and Power Plants, 1988, pp. 436–450.
236. Wu, T.M., Lee, J.Y., A Large Scale Implementation of Human Factors Engineering for the Lungmen Nuclear Power Project, Proceedings of the 4th American Nuclear Society International Topical Meeting on Nuclear Plant Instrumentation, Controls and Human–Machine Interface Technology, 2004, pp. 1–10.
237. Yan, X., Milgram, P., Doyle, D.J., Two Classes of Problem Solving Situations in Managing Complex Systems, Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1993, pp. 529–533.

238. Yean-Chuan Y., Lin,T.Z ., Chung, J.S., Der-Yu H., Lessons Learned from Reviewing a Plant-Specific Reliability Analysis, Proceedings of the International Reliability, Availability, Maintainability Conference for the Electric Power Industry, 1988, pp. 452–457.
239. Yip, W. T., Chan, K.C.C, Unified Human–Computer Interaction Requirements Analysis Framework for Complex Socio-technical Systems, International Journal of Human–Computer Interaction, Vol. 26, No. 1–3, 2010, pp. 1–21.
240. Yoshimura, S., Takayanagi, H., Study on Modeling of Operator's Learning Mechanism, Proceedings of the IEEE International Conference on Systems, Man, and Cybernetics, 1999, pp. 721–726.
241. Yutaka F., Kazuo F., Shunsuke, K, Identification of Causes of Human Errors in Support of the Development of Intelligent Computer-Assisted Instruction Systems for Plant Operator Training, Reliability Engineering and System Safety, Vol. 47, 1995, pp. 75–84.
242. Zhao, T., et. al, Based on Multi-Agent Optimize the Operation of the Power Plant Unit of Assessment Management System, IET Seminar Digest, Vol. 1, No.3, 2008, pp. 214–219.
243. Zhonaghai, Z, Lin, F., Hongfa, D., Incremental Evaluation Method—An Integrated Method to Assess Urban Energy System, Proceedings of the International Conference on Management and Service Science, 2010, pp. 5–6.
244. Zhuravyov, G.E., Sakov, B.A., Ergonomic and Psychological Provisions of a Power Plant, Proceedings of the Triennial Congress of the International Ergonomics Association and the Annual Meeting of the Human Factors and Ergonomics Association, 2000, pp. 831–834.
245. Zizzo, D., Gutierrez, R., Yu, K., Human Factors Verification of the Advanced Nuclear Plant Control Room Design, Proceedings of the Annual Joint ISA POWID/EPRI Controls and Instrumentation Conference, 2008, pp. 252–263.