7

Human Reliability

7.1 INTRODUCTION

Numerous systems are interconnected by human links. In the earlier reliability analysis, attention was directed only to equipment, and reliability of the human element was neglected.

Williams [94] recognized this shortcoming in the late 1950s and pointed out that realistic system reliability analysis must include the human aspect. Ever since the beginning of the last decade there has been a considerable interest in human-initiated equipment failures and their effect on system reliability.

According to reference 50 about 20–30 percent of failures, directly or indirectly are due to human error. Furthermore, according to reference 19 about 10–15 percent of the total failures are directly related to human errors. These are mainly due to wrong actions, maintenance errors, misinterpretation of instruments, and so on.

Subsequent work by others is listed in Section 7.10. This research deals mainly with the human error data banks, human error classification schemes, determining the significance of errors to system operation, human error allocation, and human reliability modeling in continuous time domain.

7.1.1 Human Reliability Definition

According to reference 49, human reliability is defined as the probability that a job or task will be successfully completed by personnel at any required stage in system operation within a required minimum time (if the time requirement exists).

7.1.2 Human Error

Human error is defined [19] as a failure to perform a prescribed task (or the performance of a prohibited action), which could result in damage to equipment and property or disruption of scheduled operations. In real life most systems require some human participation irrespective of the degree of automation. It is said that wherever people are involved, errors will be

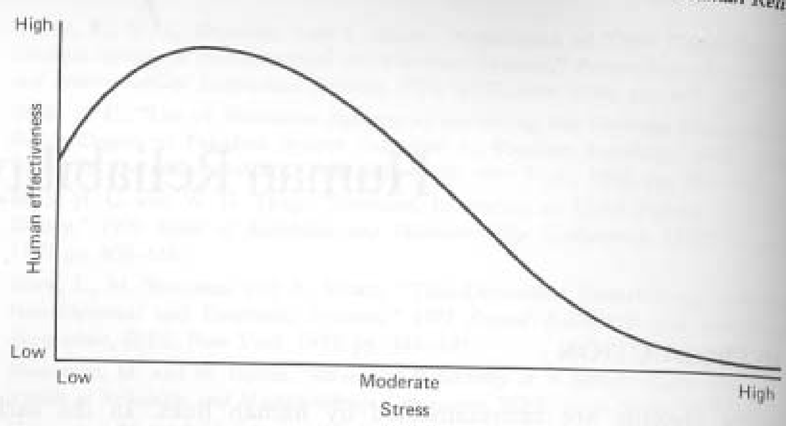

Figure 7.1 A hypothetical human effectiveness-stress curve.

made. These errors occur regardless of their training, skill, or experience. Therefore, predicting equipment reliability without considering human reliability will not present a true picture of that reliability.

7.2 HUMAN STRESS-PERFORMANCE EFFECTIVENESS

According to reference 19, the human performance and stress follow the relationship shown in Figure 7.1. This relationship shows that the human error rate for a particular task follows a curvelinear relation to the imposed stress. At a very low stress, the task is dull and unchallenging; therefore most operators will not perform effectively and the performance will not be at the optimal level. When the stress is at a moderate level, the operator performs at his optimum level. The moderate level may be interpreted as high enough stress to keep the operator alert. At a still higher stress level, the human performance begins to decline. This decline is mainly due to fear, worry, or other types of psychological stress. It follows from Figure 7.1 that at the highest stress level, the human reliability is at its lowest level.

7.3 CONCEPT OF HUMAN ERROR

According to reference 33, a human error occurs if any one of the following happens:

1. The operator or any human pursues a wrong goal.
2. The required goal is not met because the operator acted wrongly.
3. The operator fails to act in the moment of need.

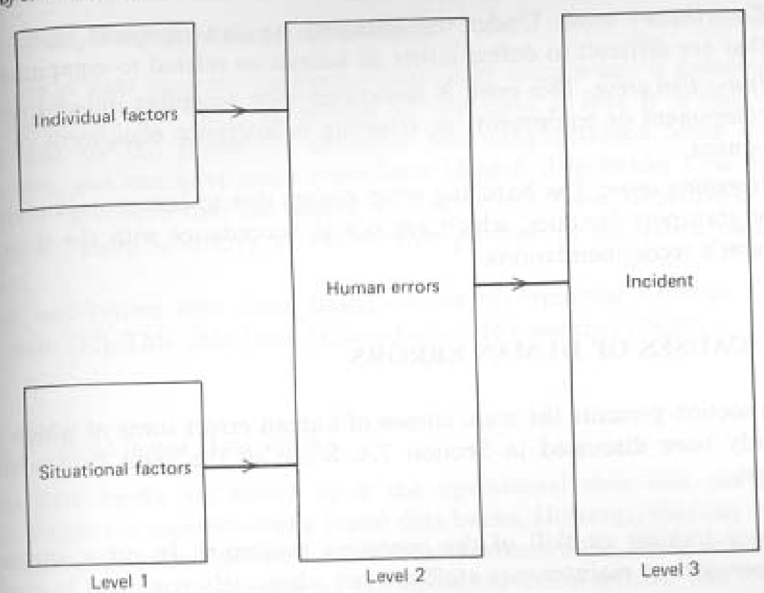

Figure 7.2 Levels of human error.

The human errors may be divided into three levels as shown in Figure 7.2. The situation may be corrected at each level of human error, shown in Figure 7.2. For example future human errors may be prevented at level 1. At level 2 a future incident can be avoided by correcting the wrong action due to human error. In the case of level 3 one could prevent the same situation from occurring again.

7.4 TYPES OF HUMAN ERROR

The author of reference 50 has categorized the human errors as follows:

1. *Design error.* This error results from inadequate design. For example, the controls and displays are so far apart that an operator finds difficulty in using both of them effectively.
2. *Operator error.* This occurs if the operating personnel fail to follow correct procedures, or there is lack of correct procedures.
3. *Fabrication error.* This error occurs at the fabrication stage due to (a) poor workmanship, for example, incorrect soldering; (b) use of wrong material; (c) the fabrication is not according to the blueprint requirement.
4. *Maintenance error.* This type of error occurs in the field. It is normally due to incorrect installation or repair of the equipment.

5. *Contributory error.* Under this category we can represent those errors that are difficult to define either as human or related to equipment.
6. *Inspection error.* This error is associated with accepting out-of-tolerance component or equipment; or rejecting in-tolerance equipment or component.
7. *Handling error.* The handling error occurs due to inappropriate storage or transport facilities, which are not in accordance with the manufacturer's recommendations.

7.5 CAUSES OF HUMAN ERRORS

This section presents the main causes of human errors some of which have already been discussed in Section 7.4. Some of the main causes are as follows:

1. Poor training or skill of the operating personnel. In other words the operators or maintenance staff are not adequately equipped to perform the prescribed task.
2. Inadequate maintenance or operating procedures for the operating personnel.
3. Poor job environments, for example, accessibility, crowded space, and temperature.
4. Poor or inadequate handling of equipment or tools.
5. Poor motivation for the operators or the maintenance personnel which effects their performance from being at optimum level.

7.6 HUMAN UNRELIABILITY DATA BANKS

The material presented in this section is taken from reference 47. Therefore, the interested reader can consult this reference for further details. This paper presents a brief review of existing methods to develop human reliability data banks. The major emphasis of this publication is upon the estimation data collected from expert opinions. The author states that there is a lack of human data compared to the techniques available to predict human reliability.

The human error data banks may be divided into the following three categories:

1. Experimentally based data banks.
2. Field-based data banks.
3. Subjectively based data banks.

7.6.1 Experimentally Based Data Banks

This type of data bank is based upon laboratory sources and is gathered in the laboratory. The main advantage of this data is that it is the least influenced by the subjective elements that may produce some error. Therefore, one can have more confidence in such data banks. One must, however, be aware that no matter how carefully these data banks are developed, there is always a considerable amount of subjective element present.

The well-known data bank based on the experimental findings is the *data store* [52]. This data bank is based upon 164 selected studies.

7.6.2 Field-Based Data Banks

These data banks are based upon the operational data and are more realistic than the experimentally based data banks. However, the field-based data banks are rather difficult to establish because these banks are based upon real activities occurring in the operating environment. The results obtained from these banks are more satisfactory than those obtained from the experimental sources whose tasks are often contrived.

At present there are two noteworthy field-based data banks, which are described in references 93 and 78. The one presented in reference 93 is called the Operational Performance Recording and Evaluating Data System (OPREDS), which permits the automatic monitoring of all operator actions. However, it is only applicable to limited cases (e.g., switch actions). The other proposed data bank is called the Sandia Human Error Rate Bank (SHERB) [78].

7.6.3 Subjectively-Based Data Banks

These data banks are based upon expert opinions and have two attractive features:

1. They are comparatively easy to develop because a large amount of data can be collected from a small number of expert respondents.
2. They are cheaper to develop.

The subjective-based data is obtained by using less rigorous techniques such as DELPHI [13]. This technique narrows the guess-estimate variations of the field experts by feeding back the end result of the study to individual judges or experts. It makes them reconsider their guess-estimates until some form of consensus is arrived. This method is already effective at the Naval Personnel Research and Development Center [36].

The following requirements must be satisfied if these banks are to be used in the human reliability analysis:

1. *Validity.* A subjective data bank will contain some error. Therefore, we should be prepared to accept a somewhat lower accuracy of such data banks as compared to the experimental data ones.
2. *Expert Judgement.* The subjective data should be collected only from those personnel who are recognized as highly skilled to perform tasks in question and in addition, have observed others performing such tasks. For example, it is better to obtain data from operators rather than the human reliability experts.
3. *Performance Dimensions.* The technique to be used should be decided very carefully, keeping in mind the dimensions of the performance being estimated.
4. *Judgment Description Level.* The performance-shaping factors associated with these estimates must be determined at an early stage. Furthermore, the types of errors to be included for a particular task should be clarified.
5. *Procedure Specification.* To obtain subjective estimates, the applicable procedure should be specified, for example, whether it is DELPHI or paired comparisons.

The main advantage of this type of data bank is the coverage of a wide range of parameters for which failure data is required.

7.7 HUMAN RELIABILITY MODELING IN CONTINUOUS TIME DOMAIN

The material presented in this section is based on reference 63. Some of the typical examples of such tasks are scope monitoring, aircraft maneuvering, and missile countdown. This type of modeling is analogous to the classical reliability modeling.

The generalized human performance reliability function for continuous time tasks is derived in the following section. (Note: for discrete case consult reference 62.)

7.7.1 *Human Performance Reliability Function in Continuous Time Domain*

Although all human tasks are not in continuous time domain, tasks such as vigilance, monitoring, and tracking fall in this category. In the case of continuous tasks, the probability of occurrence of human error in the time

interval, (δt given E_1) is given by

$$P(E_2/E_1)=e(t)\,\delta t \tag{7.1}$$

where $e(t)$ = the human error rate at time t; this is analogous to the hazard rate, $z(t)$, in the classical reliability theory

E_1 = an errorless performance event of duration t

E_2 = an event that the human error will occur in time interval $(t, t+\delta t)$

The joint probability of the errorless performance may be expressed as follows:

$$P(\bar{E}_2/E_1)p(E_1)=P(E_1)-P(E_2/E_1)P(E_1) \tag{7.2}$$

where $\bar{E}_2$ denotes the event that error will not occur in interval $[t, t+\delta t]$. The above equation may be rewritten as

$$R_h(t)-R_h(t)P(E_2/E_1)=R_h(t+\delta t) \tag{7.3}$$

where $R_h(t)$ is human reliability. Expression 7.2 represents an errorless performance probability over intervals $[0, t]$ and $[t, t+\delta t]$.

By substituting (7.1) into (7.3) we get

$$\frac{R_h(t+\delta t)-R_h(t)}{\delta t}=-e(t)R_h(t) \tag{7.4}$$

In the limiting case, the above expression becomes

$$\frac{dR_h(t)}{dt}=-e(t)R_h(t) \tag{7.5}$$

To solve the differential equation we may write for known initial conditions

$$\int_0^t e(t)\,dt=-\int_1^{R_h(t)}\frac{1}{R_h(t)}\,dR_h(t) \tag{7.6}$$

The solution to the differential equation (7.5) is

$$R_h(t)=e^{-\int_0^t e(t)\,dt} \tag{7.7}$$

This is the general expression to compute human reliability.

7.7.2 *Reliability Quantifiers for Time Continuous Human Performance Tasks*

These parameters are analogous to the classical reliability theory. Time continuous human performance task quantifiers are defined as follows:

Mean Time to Human Initiated Failure (MTHIF). This index is analogous to the mean time to failure (MTTF) in the classical reliability theory. This quantifier is used for the time continuous tasks such as undershooting a landing aircraft or overpressurizing a missile fuel tank.

Mean-Time-to-First-Human-Error (MTFHR). This quantifier is analogous to the mean time to first failure (MTTFF) in the classical theory. The MTFHR may be used for cases where the occurrence of the first human error is highly critical.

Mean Time Between Human Errors (MTBHE). This is known as the mean time between human errors. It is directly translated from the mean time between failure (MTBF) as known in the classical reliability theory. This indicator may be used where the human errors are not so critical. For example, it may be used for measuring the occurrence of defective parts due to human errors at a production line.

7.7.3 *Experimental Justification of the Time Continuous Human Performance Model*

To justify time continuous task model discussed earlier, the authors of reference 63 have developed a simple model to obtain human error data. The main feature of this experiment was to observe a clock-type light display. The operator was required to respond to a failed light event by pressing a hand held switch.

The following types of data was collected from this experiment:

1. *Miss error.* The operator (subject) did not detect the failed light.
2. *False alarm error.* The operator (subject) responds in such a way as if a failed-light event has occurred when it did not occur in reality.

The failure data collected from this study was analyzed by graphical technique and the Kolmogorov-Smirnov d statistic.

This study reported that the human error rate is a time variant. Furthermore, this experiment tested the following types of errors:

1. Times to first miss error.
2. Times to false alarm error.
3. Combined miss and false alarm error.

The Weibull, gamma, and log-normal density functions emerged as the representative distributions for the goodness of fit.

7.7.4 *Human Performance Effectiveness Function (Correctability) in Time Continuous Domain*

The correctability function $C_h(t)$ concerns with the correction of the self-generated human errors. In reference 63, it is defined as the probability that a task error will be corrected in time t subject to stress constraint inherent in the nature of the task and its environment. In other words, the correctability function may be defined as

$$C_h(t) = P\,\{\text{correction of error in time } t/\text{stress}\} \tag{7.8}$$

The time derivative of not-correctability function $\overline{C}_h(t)$ may be defined as

$$\overline{C}_h'(t) = -\frac{1}{N} N_C'(t) \tag{7.9}$$

where the prime denotes differentiation with respect to time t. N is the total number of times task correction accomplished after time t. $N_{\overline{C}}(t)$ is the number of times task not completed after time t.

Equation 7.9 may be rewritten in the following form:

$$N\{N_{\overline{C}}(t)\}^{-1}\overline{C}_h'(t) = N_C'(t)\{N_{\overline{C}}(t)\}^{-1} \tag{7.10}$$

The right-hand side of (7.10) represents instantaneous task correction rate $C_R(t)$. Hence, (7.10) may be rewritten as

$$\{\overline{C}_h(t)\}^{-1}\overline{C}_h'(t) + C_R(t) = 0 \tag{7.11}$$

By solving the above differential equation for given initial conditions we get

$$\overline{C}_h(t) = e^{-\int_0^t C_R(t)\,dt} \tag{7.12}$$

since

$$C_h(t) + \overline{C}_h(t) = 1$$

Therefore,

$$C_h(t) = 1 - e^{-\int_0^t C_R(t)\,dt} \tag{7.13}$$

The above equation is a general expression. It holds for both constant and instantaneous correction rates. The experimental results with data, for the above function are presented in reference 63. This experiment dealt with the operation of a standard *E*-type manual control stick grip, subject to two degrees of freedom representing the pitch and roll motions of an aircraft in response to the instrument altitude pointer movement.

These results indicate that for both vigilance and compensatory tracking tasks, the Weibull density function is a suitable fit for the time to first error correction. On the other hand, the log-normal is equally applicable for the time for correction of errors.

7.8 HUMAN ERROR PREDICTION TECHNIQUE

This technique is relatively well known among the human reliability experts. It is known as THERP (technique for human error rate prediction). THERP, which is discussed in detail in reference 79, is based upon the classical analysis method. The basic steps associated with THERP are

1. List main system failure events.
2. List and analyze human related functions.
3. Obtain estimates for the human error rates.
4. Determine human error effects on the system failure events in question.
5. Make necessary recommendations and necessary changes in the system in question. At the end compute new failure rates for the system under study.

7.8.1 Probability Tree Analysis

This is one of the main techniques for human reliability analysis. Success or failure of each critical human action or associated event is assigned a conditional probability. The outcome of each event is represented by the branching limbs of the probability tree. The total probability of success for a particular operation is obtained by summing up the associated probabilities with the end point of the success path through the probability tree diagram. This technique, with some refinement, can include factors such as time stress, emotional stress, interaction stress, interaction effects, and equipment failures.

Some of the advantages of this technique are as follows:

1. It serves as a visibility tool.
2. The mathematical computations are simplified, which in turn decrease the probability of occurrence of errors due to computation.
3. The human reliability analyst can estimate conditional probability readily, which may otherwise be obtained from the complicated probability equations.

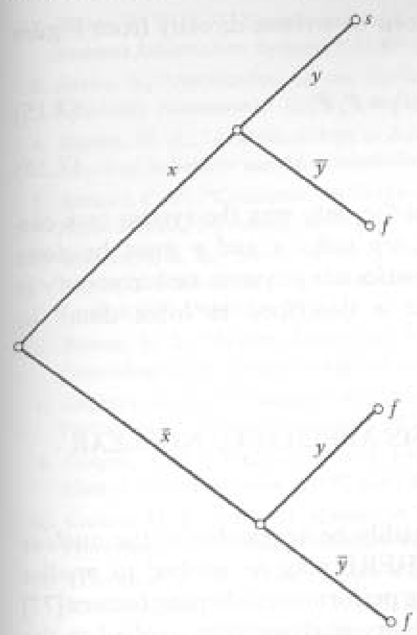

Figure 7.3 A hypothetical task probability tree diagram.

Example. Assume that an operator performs two tasks, say x and y (the task x is performed before y). In addition assume that tasks x and y can be performed either correctly or incorrectly. In other words the incorrectly performed tasks are the only errors that can occur in this situation. Draw the probability tree for this example and obtain the overall system probability to perform incorrect task. In this example we assume that the probabilities are statistically independent.

This example states that the operator can perform task x correctly or incorrectly. Later, the operator may proceed to perform task y which also has two different possibilities (correct and incorrect). The following notations were used to define the probability tree diagram as shown in Figure 7.3:

P_s = probability of task success
P_f = probability of failure to accomplish required task
s = success
f = failure
P_x = probability of success in performing task x
P_y = probability of success in performing task y
$P_{\bar{x}}$ = probability of failure to perform task x
$P_{\bar{y}}$ = probability of failure to perform task y

The probability of success, P_s, can be written from Figure 7.3 as follows:

$$P_s = P_x \cdot P_y \tag{7.14}$$

Similarly, the failure probability, P_f, can be written directly from Figure 7.3 as follows:

$$P_f = P_x P_{\bar{y}} + P_{\bar{x}} P_y + P_{\bar{x}} P_{\bar{y}} \quad (7.15)$$

$$= 1 - P_x P_y \quad (7.16)$$

It can be noticed from Figure 7.3 that the only way the system task can be performed successfully is that both the tasks x and y must be done correctly. Therefore the probability of performing system task correctly is simply given by $P_x P_y$. This technique is described in more detail in reference 79.

7.9 HUMAN RELIABILITY ANALYSIS APPLIED TO NUCLEAR PLANTS

There is no single technique that can readily be applicable to the nuclear power plants. The technique such as THERP may be applied to predict human reliability. However, the following performance-shaping factors [77] are to be considered in the human reliability analysis when applied to the nuclear power plant.

1. Training and practice quality.
2. Quality and existence of written instructions as well as the method of proper usage.
3. Quality of human engineering as applied to the nuclear power plant controls and displays.
4. Type of the display feedback. For example, there may be too many displays competing for the operator attention.
5. Human action independence.
6. Redundancy concerning humans.
7. Psychological stress.

Once these shaping factors have been considered, one should proceed to estimate the human error rate. Human error rate estimates then should be included in the Fault Tree Analysis. This type of analysis is probed in depth in reference 61.

REFERENCES

1. Altman, J. W., "Classification of Human Errors," In: Edited by W. B. Askren, *Proceedings Symposium Reliability of Human Performance in Work*, Wright-Patterson AFB, Ohio, Rep AMRL-TR-67-88, 1967.

2. Bailey, R. W., S. T. Demers, and A. I. Lebowitz, "Human Reliability in Computer-Based Business Information Systems," *IEEE Trans. Reliability*, **R-22**, pp. 140–147 (Aug. 1973).
3. Baron, S., "Application of the Optimal Control Model for the Human Operator to Reliability Assessment," *IEEE Trans. Reliab.*, **22**, 157–164 (August 1973).
4. Barone, M. A., "A Methodology to Analyse and Evaluate Critical Human Performance," *Annals of Reliability and Maintainability Conference*, IEEE, New York, 1966.
5. Birdsall, C. R., "Comments on Psychological Reliability, Man-Machine Systems," *IEEE Trans. Reliab.*, November 1971. pp. 260–261.
6. Blanchard, R. E., "Survey of Navy User Needs for Human Reliability Models and Data Report No. 102-1," Naval Underwater Systems Center, New London Laboratory, New London, CT, December 1972.
7. Brown, E. S., "System Safety and Human Factors: Some Necessary Relationships," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1974.
8. Celinski, O. and M. Master, "An Activity Model for Predicting the Reliability of Human Performance," *Annual Reliability and Maintainability Symposium*, 1974.
9. Cooper, J. I., "Human-Initiated Failures and Malfunction Reporting," *IRE Trans. Human Factors Electron.*, **HFE**, 104–109 (September 1961).
10. Cornog, D. Y. and A. H. Ruder, "A Postal Service Field Evaluation of Letter Sorting," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1977.
11. Crawford, B. M., "The Human Component in Systems," *Annals of Reliability and Maintainability*, 1971.
12. Cunningham, C. E. and W. Cox, *Human Factors in Maintainability*, *Applied Maintainability Engineering*, Wiley-Interscience, New York, 1972.
13. Dalkey, N. and F. Helmer, "An Experimental Application of the DELPHI Method to the Use of Experts," *Manag. Sci.*, **9**, 458–467, (1963).
14. De Callies, R. N., "Human Reliability in the Operation of V/Stol Aircraft," *Annals of Reliability and Maintainability Conference*, 1966.
15. Drury, C. G., S. G. Schiro, and S. J. Czaja, "Human Reliability in Emergency Medical Response," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1977.
16. Drury, C. G. and J. G. Fox, *Human Reliability in Quality Control*, Halstead, New York, 1976.
17. Fishburn, P., A. Murphy, and H. Isaacs, "Sensitivity of Decisions to Probability Estimation Errors: A Re-Examination," *Oper. Res.*, **16**, 254–267 (1968).
18. Gael, S., "Improving Output Through Job Performance Evaluation," *Annual Reliability and Maintainability Symposium*, 1978.
19. Hagen, E. W., Editor, "Human Reliability Analysis," *Nucl. Safety*, **17**, 315–326 (1976).
20. Halpin, S. M. and E. M. Johnson, "Cognitive Reliability in Manned Systems," *IEEE Trans. Reliability*, **22**, 165–169 (1973).
21. Huston, R. L., "Human Reliability on Man-Machine Interactions," *Annual Reliability and Maintainability Symposium*, 1974.
22. Inaba, K. and R. Matson, "Measurement of Human Errors with Existing Data," *Seventh Annual Reliability and Maintainability Conference*, ASME, New York, 1968.
23. Irwin, I. A., J. J. Levitz, and A. M. Freed, "Human Reliability in the Performance of Maintenance," *Proceedings of the Symposium on Quantification of Human Performance*, Electronic Industries Association and University of New Mexico, Albuquerque, New Mexico, August 1964.
24. Johnson, E. M., R. C. Cavanagh, R. L. Spooner, and M. G. Samet, "Utilization of Reliability Measurements in Bayesian Inference: Models and Human Performance," *IEEE Trans. Reliab.* **R-22**, 1973.

25. Jones, D. M., "The Need for Quantification in Human Factors Engineering," *Sixth Reliability and Maintainability Conference*, 1967.

26. Juran, J. M., "Operator Errors—Time for a New Look," *Qual. Control*, **1**, (1968), pp. 9–11.

27. Katter, R. V., "On Managing the Present Through Efficient Use of the Past," *Sixth Reliability and Maintainability Conference*, 1967.

28. Kaufman, R. A., T. F. Oehrlein, and M. L. Kaufmann, "Predicting Human Reliability—Implications for Operations and Maintenance in Space," National IAS-ARS Joint Meeting, June 13–16, 1961.

29. Keenan, J. J., "Interactionist Models of the Varieties of Human Performance in Complex Work Systems," *Sixth Reliability and Maintainability Conference*, 1967.

30. Kelly, C. W. and S. Barclay, "Improvement of Human Reliability Using Bayesian Hierarchical Inference," *Annual Reliability and Maintainability Symposium*, 1974.

31. Koppa, R. J. and G. G. Hayes, "Determination of Motor Vehicle Characteristics Affecting Driver Handling Performance," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1976.

32. Kraft, J. A., "Mitigating of Human Error Through Human Factors Design Engineering," *Annual Reliability and Maintainability Conference*, ASME, New York, 1968.

33. Kragt, H., "Human Reliability Engineering," *IEEE Trans. Reliability*, **R-27**, 195–201, (1978).

34. Lamb, J. C. and K. E. Williams, "Prediction of Operator Performance for Sonar Maintenance," *IEEE Trans. Reliab.*, **R-22**, 131–134 (1973).

35. Lamb, J. C., "A Test of a Basic Assumption of Human Performance Modeling," *Annual Reliability and Maintainability Symposium*, 1972.

36. Larsen, O. A. and S. I. Sander, "Development of Unit Performance Effectiveness Measures Using DELPHI Procedures," NPRDC-TR-76-12, Navy Research and Development Center, San Diego, CA, September 1975.

37. LaSala, K. P., A. I. Siegel, and C. Sontz, "Allocation of Man-Machine Reliability," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1976.

38. LaSala, K. P., A. I. Siegel, and C. Sontz, "Man-Machine Reliability—A Practical Engineering Tool," *Annual Reliability and Maintainability Symposium*, 1978.

39. Lees, F. P., "Quantification of Man-Machine System Reliability in Process Control," *IEEE Trans. Reliab.*, **R-22**, (1973).

40. Lees, F. P., "Man-Machine System Reliability, In: E. Edwards and F. P. Lees," *Man and Computer in Process Control*, The Institution of Chemical Engineers, London, England, 1973.

41. Lincoln, R. S., "Human Factors in Attainment of Reliability," *IRE Trans. Reliability Qual. Contr.* (1962). pp. 97–103.

42. Lincoln, R. S., "Human Factors in the Attainment of Reliability," *IRE Trans. Reliability Contr.* (1960). pp. 97–103.

43. Majesty, M. S., "Personnel Sub-System Reliability for Aerospace Systems," *Proceedings IAS National Aerospace Systems Reliability Symposium*, 1962.

44. Manz, G. W., "Human Engineering: Aids to Smooth Operation," *Nucl. Safety*, **18**, 223–227 (1977).

45. Meister, D., "A Critical Review of Human Performance Reliability Predictive Methods," *IEEE Trans. Reliab.*, **22**, 116–123 (1973).

46. Meister, D., "Comparative Analysis of Human Reliability Models," AD 734 432, NTIS, Springfield, Virginia, USA 1971.

47. Meister, D., "Subjective Data in Human Reliability Estimates," *Annual Reliability and Maintainability Symposium*, 1978.

48. Meister, D. and R. G. Mills, "Development of Human Performance Reliability Data System," *Annals of Reliability and Maintainability Symposium*, 1972.

49. Meister, D., "Human Factors in Reliability," In: Edited by W. G. Ireson, *Reliability Handbook*, McGraw-Hill, New York, 1966.

50. Meister, D., "The Problem of Human-Initiated Failures," *Eighth National Symposium on Reliability and Quality Control*, 1962.

51. Muller, P. F., "Potential Damage Evaluation: A Method for Determining the Potential for Human-Caused Damage in Operating Systems," *Proceedings of the Reliability and Maintainability Conference*, 1968.

52. Munger, S. J., et al., R. W. Smith, D. Payne, "An Index of Electronic Equipment Operability: Data Store," Report AIR-C43-1/62-RP (1), American Institute for Research, Pittsburgh, PA, January 1962.

53. Nahvi, M. J., "Reliability of Human Visual Signal Detection in the Presence of Noise," *IEEE Trans. Reliability*, **R-23**, 326–331 (1974).

54. Nawrocki, L. H., M. H. Strub, and R. M. Cecil, "Error Categorization and Analysis in Man-Computer Communication Systems," *IEEE Trans. Reliability*, **R-23**, (1978).

55. Page, H. J., "The Human Element in the Maintenance Package," *Eighth National Symposium on Reliability and Quality Control*, 1962.

56. Peters, G. A. and T. A. Hussman, "Human Factors in Systems Reliability," *Human Factors*, **1**, 38–50 (1959).

57. Pontecorvo, A. B., "A Method of Predicting Human Reliability," *Annual Reliability and Maintainability Symposium*, 1965.

58. Rabideau, G. F., "Prediction of Personnel Sub-System Reliability Early in the System Development Cycle," *Proceedings IAS National Aerospace Systems Reliability Symposium*, 1962.

59. Ramsey, J. D., "Reliability and Comparability of Heat Exposure Indices," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1976.

60. Rasmussen, J., "The Role of the Man-Machine Interface in Systems Reliability," *NATO Generic Conference*, Liverpool, England, 1973.

61. Reactor Safety Report, WASH, 1400, Apx III and IV, NTIS, Springfield, IL, 1975.

62. Regulinski, T. L., "Human Performance Reliability Modeling in Time Continuous Domain," *Proceedings NATO Generic Conference*, Liverpool, England, 1973.

63. Regulinski, T. L. and W. B. Askren, "Mathematical Modeling of Human Performance Reliability," *Proceedings of Annual Symposium on Reliability*, 1969.

64. Regulinski, T. L., "Stochastic Modeling of Human Performance Effectiveness Functions," *Annual Reliability and Maintainability Symposium*, 1972.

65. Regulinski, T. L., "On Modeling Human Performance Reliability," *IEEE Trans. Reliab.* **R-22**, 114–115 (1973).

66. Rigby, L. V. and A. D. Swain, "Effects of Assembly Error on Product Acceptability and Reliability," *Proceedings of the Seventh Annual Reliability and Maintainability Conference*, 1968.

67. Rigby, L. V., "Why Do People Drop Things," *Quality Progr.*, 16–19 (1973).

68. Robinson, J. E., W. E. Deutch, and J. G. Rogers, *Human Factors*, **12**, 256–267 (1970).

69. Schum, D. and W. Ducharme, "Comments on the Relationship Between the Impact and the Reliability of Evidence." *Organiz. Behav. Human Perf.*, **6**, (1971).

70. Schum, D. A. and P. E. Pfeiffer, "Observer Reliability and Human Inference," *IEEE Trans. Reliability*, **22**, (1973).

71. Siegel, A. E., J. Jay Wolf, and M. R. Lautman, "A Family of Models for Measuring Human Reliability," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1975.

72. Siegel, A. I., "A Method for Predicting the Probability of Effective Equipment Maintenance," *Annual Reliability and Maintainability Symposium*, 1972.

73. Smith, C. O., *Introduction to Reliability in Design*, McGraw-Hill, New York, 1976.

74. Sontz, C. and J. C. Lamb, "Predicting System Reliability from Human Data," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1975.

75. Sriyananda, H. and D. R. Towill, "Prediction of Human Operator Performance," *IEEE Trans. Reliab.*, **R-22**, 145–156 (1973).

76. Street, R. L., "Reducing Maintenance Error by Human Engineering Techniques," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1974.

77. Swain, A. D. and H. E. Guttmann, "Human Reliability Analysis Applied to Nuclear Power," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1975.

78. Swain, A. D., "Development of a Human Error Rate Data Bank," *Proceedings US Navy Human Reliability Workshop*, NAVSHIPS 0967-412-4010, February 1977.

79. Swain, A. D., "Shortcuts in Human Reliability Analysis, Generic Techniques in Systems Reliability Assessment," Noordhoff, Leyden, 1974.

80. Swain, A. D., "The Human Element in System Development," *Annual Symposium on Reliability*, 1970.

81. Swain, A. D., "Human Factors in Design of Reliable Systems," Sandia Corporation, Report SC-R-748, February 1964.

82. Swain, A. D., "Reliable Systems vs. Automatic Testing," *Proceedings of the Ninth National Symposium on Reliability and Quality Control*, 1963.

83. Swain, A. D., "Overview and Status of Human Factors Reliability Analysis," *Proceedings of the Eighth Reliability and Maintainability Conference*, New York, July 1969.

84. Swain, A. D., "A Method for Performing Human Factor Reliability Analysis," Sandia Corporation, SCR-685, August 1963.

85. Swain, A. D., "Some Problems in the Measurement of Human Performance in Man-Machine Systems," *Human Factors*, **6**, pp. 687–700, (1964).

86. Swain, A. D., "Design of Industrial Jobs a Worker Can and Will Do," *Human Factors*, **15**, 129–136 (1973).

87. Swain, A. D., "An Error-Cause Removal Program for Industry," *Human Factors*, **15**, 207–221 (1973).

88. Teichner, W. H., "Prediction of Human Performance," *Annual Reliability and Maintainability Symposium*, 1972.

89. Thompson, C. W. N., "Model of Human Performance Reliability in Health Care Systems," *Annual Reliability and Maintainability Symposium*, 1974.

90. Topmiller, D. A. and N. M. Aume, "Computer-Graphic Design for Human Performance," *Annual Reliability and Maintainability Symposium*, 1978.

91. Topmiller, D. A., "Human Factors and Systems Effectiveness," *Annals of Reliability and Maintainability Conference*, 1966.

92. Towill, D. R., "Recent Developments in the Prediction of Human Operator Performance," *1973 NATO Generic Studies Conference*, Noordhoff, Leyden, 1976.

93. Urmston, R., "Operational Performance Recording and Evaluation Data System (OPREDS)," Descriptive Brochures, Code 3400, NAVY Electronics Laboratory Center, San Diego, CA, November 1971.

94. Williams, H. L., "Reliability Evaluation of the Human Component in Man-Machine Systems," Electrical Manufacturing, April 1958.

95. Yun, K. W. and F. E. Kalivoda, "A Model for An Estimation of the Product Warranty Return Rate," *Proceedings of the Annual Reliability and Maintainability Symposium*, 1977.