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Advances in human reliability analysis methodology. Part II: PC-based HRA software

P. Moieni, A. J. Spurgin

Accident Prevention Group, 16980 Via tazon, Suite 110, San Diego, California 92127, USA

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A. Singh

Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, California 94303, USA

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This paper, in two parts, summarizes some of the advancements made in the area of human reliability analysis (HRA) in the past decade. The paper focuses on the HRA program sponsored by the Electric Power Research Institute (EPRI) since 1982 as part of an effort to better understand the role of operators in safe operation of nuclear power plants (NPPs) and advance the state-of-the-art in HRA. Many technical reports have been published and numerous papers have been presented in national and international conferences on the various EPRI HRA projects. This paper is an attempt to summarize a decade of research in this area with an emphasis on recent advancements made towards development of a simulator-based HRA methodology using data from NPP simulators. HRA frameworks, models, data and computer codes are discussed, and areas for further research are pointed out. This paper discusses the PC-based software developed to facilitate the process of simulator data collection and analysis as well as the assessment of human reliability.

1 INTRODUCTION

It is well recognized that humans play an important role in the safe operation of nuclear power plants (NPPs) and other complex industrial establishments, such as chemical plants, airlines, railways, etc. Studies of actuarial records of various industrial experience have shown that human–system interactions are extremely important to safety.[1–4] This conclusion is also supported by review and analysis of major accidents occurred in highly-technical facilities. Examples are Three-Mile Island Unit 2 (TMI-2), Chernobyl, Challenger, Bhopal, Piper Alpha accidents that involved human deficiencies in various areas of management, operations, maintenance and training.[5]

A widely used method of assessment of risk of nuclear power plants is probabilistic risk (or safety) assessment (PRA or PSA). It provides a quantitative measure of plant safety. Assessments made in various generic and plant-specific PRAs for NPPs to date provide further corroboration for the importance of human interactions.

Human–system or simply human interactions (HIs) is the term that describes all interfaces between humans and the system (e.g. NPPs). Included in the definition are the activities of the control room operators, local equipment or auxiliary operators, mechanical/electrical maintenance personnel, and instrumentation and control technicians. It is noted that the terms 'human error' and 'human failure' have also been used in HRA literature and in this paper, particularly, when it comes to the quantification of HIs.

The human reliability analysis in the context of a PRA is an attempt to model human–system interactions and predict the impact of such interactions on the system's safety and reliability. When it comes to complex systems such as NPPs that involve a large number of HIs in every phase of the plant operations, then HRA becomes an extremely important element of PRA for a realistic assessment of plant safety.

Human reliability is a complex subject which cannot be addressed by rather straightforward reliability models like those for components and systems. The study of how humans affect the reliability of complex systems is a challenging task for engineers, psychologists, and human factors experts. Some HRA experts have recognized the need for a major change and development of second generation HRA methods.[6] In the authors' opinion, HRA is a developing technology, currently at the threshold of change. The change appears to be a move from the purely expert judgement-based quantification methods towards a more balanced approach using a combination of experimentally derived data and insights (using both large-scale training simulators and small-scale simulations) coupled with the use of formalized expert judgement methods.

Having realized the importance of human reliability on the safe operation of NPPs, as well as the need for advancement of the state-of-the-art in HRA, EPRI launched a human reliability program in 1982. This program has covered important areas of development of a structured HRA framework, to be used in PRAs, a benchmark of the framework and HRA quantification methods. These developments were supported by multi-year data collection efforts and development of computer software to facilitate both the processing of data collected using NPP training simulators and assessment of human reliability.

Part I of the paper covered, in detail, the areas of HRA frameworks, models and data (see this issue, pp. 27–55). This part briefly describes the development of two personal computer (PC)-based HRA codes. Details on these codes may be provided in a future article. A general discussion of use of PCs in the area of HRA can be found in Ref. 7. Section 2 describes a PC-based code developed for automatic data collection and analysis using NPP simulators to support HRA and other related activities. Section 3 presents a PC-based code developed to support performing HRA using methods described in Part I of this paper.

It should be noted that some of the source documents for this paper are the EPRI licensable reports, which are available to the public at some cost.

2 OPERATOR RELIABILITY ASSESSMENT SYSTEM (OPERAS)

2.1 Introduction

This section describes the design and testing of an automated simulator data collection and analysis software called Operator Reliability Assessment System (OPERAS).[8,9] The data collection and analysis approach developed during the EPRI sponsored operator reliability experiments (ORE) project[10,11] could be used to help in human reliability analysis, in training by supplying data on crews' performance, in evaluating procedures, human factors improvements and operator aids. However, the approach needed to be automated, since it was too labor intensive. As a result, the ORE data collection and analysis methodology was automated as OPERAS. Data collected from the simulator include plant variable data such as reactor temperature, pressure, etc., times at which malfunctions are simulated, annunciators are activated, and when operators take actions. Data is also gathered on accuracy and completeness of actions from observations of crews during the accident and from crew debriefs following transients. The data can be used for PRA studies to estimate human error probabilities and for procedure validation purposes. This data can also be used to assess the impact of procedures, team skills, operator aids and human factors modifications to control boards.

2.2 Design

The prime objective of the design of OPERAS was to make available a PC-based tool to collect data from plant simulators and observers and perform the analyses in an efficient and cost effective manner. The requirements for the data to be collected and analyses to be performed were derived from experiences gained during the ORE project. Figure 1 shows a schematic arrangement of OPERAS indicating input from both the simulator (annunciator states, plant variables, operator actions and malfunctions) and observers (use of procedures, indications and controls) and information from debriefs. OPERAS also contains databases, carries out analyses and produces plots, tables and statistics.

The concept was to base OPERAS on an IBM 386 PC connected to a plant simulator. Data on the scenario and the crews' responses were to be collected by the PC, analyzed and the output to be available shortly after the training session has been completed. Various combinations of software were considered but finally, Microsoft Windows™ was chosen as the framework for information display. A 'C' language program would be used to collect the

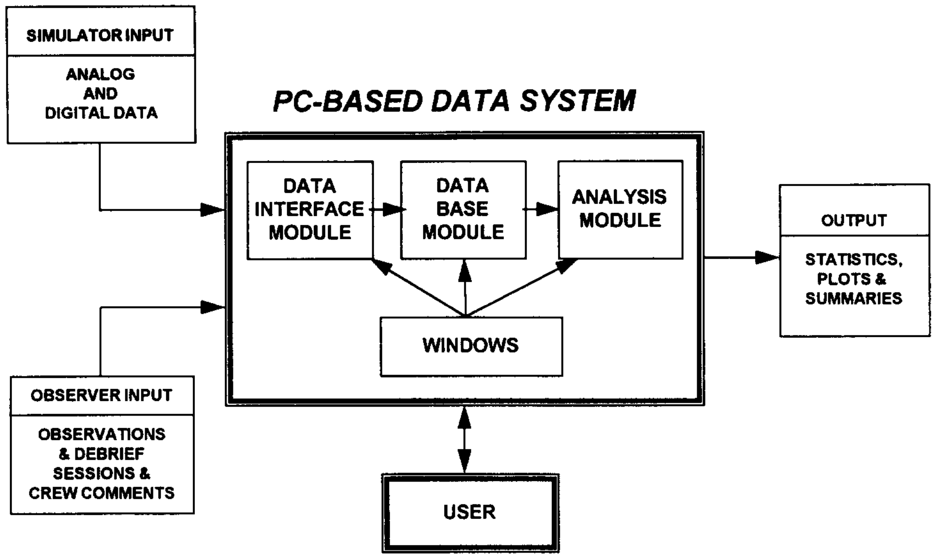

Fig. 1. Schematic of OPERAS.[8]

data from the simulator and the storage, analysis, plots and tables would be handled by using Microsoft Excel™. Another requirement of the software design was to have a system which could perform in a user friendly manner. This can be accomplished by operating in the Windows™ environment. Windows™ programs allow the user to select data from various databases for subsequent calculations or for plotting purposes. Excel™, which is a powerful spreadsheet program, can be programmed by means of macro-programs to carry out the statistical and plotting functions. The interface between the simulator and the PC is via an RS-232. The data passed over the RS-232 channel is edited and arranged so that the user can select the annunciators, operator actions and times to be analyzed.

2.3 Functions performed by OPERAS

The two main functions of OPERAS are to process simulator input data and observer input data; these data are then used to produce plots of various kinds, statistical measures, lists of deviations from procedures and difficulties with instruments and controls. Possible causes for difficulties with procedures, instruments and controls are also identified by the crews and observers and recorded for subsequent analysis. Sequence of events with their corresponding times can also be retrieved from the input data. Sequence of event data is obtained from simulator data input. The user can specify which specific information is required and the simulator input for a set of scenario runs can be examined using the same search criteria. OPERAS will then list the sequence for each scenario-crew pair with the corresponding time-line.

Table 1 lists the various kinds of plots that can be produced. Some of these plots can be produced directly after the simulator sessions are complete, whereas other plots and statistics can only be produced after a number of crew/scenarios have been run. The comparison plots and time-reliability plots fall into this latter category. Figure 2 shows a typical single variable plot versus time. Figure 3 shows a typical plot for a single variable but for four different crews. Figure 4 shows the variation in steam generator water level and pressure as a function of time with indications of plant malfunctions and operator actions. In addition to the plots, statistical measures on various types of data are also produced, such as range, mean, median, upper and lower ninety five percentile values, and standard deviation.

In addition to the simulator derived data such as variable plots, time-reliability curve (TRC) plots and sequence of operator actions, observer data is also collected and displayed for use by the training instructors. Table 2 shows a summary of observations of a crew responding to a given scenario. This

Table 1. OPERAS plot capability

- Single plant variable versus time
- A single variable for one to four scenarios (e.g. responses due to four different crews)
- Four plant variables for one scenario
- Single plant variable with specific operator actions indicated on plot
- Crews' non-response probability versus time (TRC)
- Variability in time of a group of crews performing same sequence of actions
- Order plots—variability in crew response—rank ordered

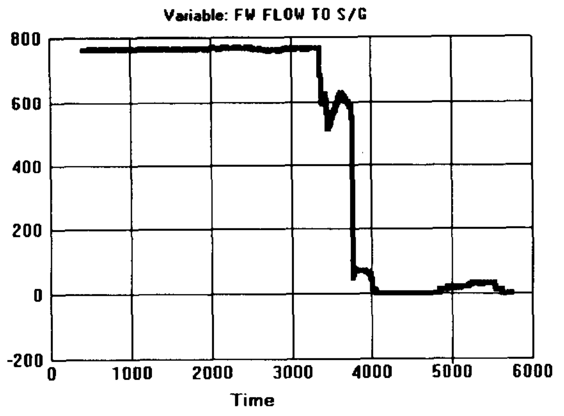

Fig. 2. Typical plot of a plant variable versus time.

information can be used to see if there are any systematic procedural areas of concern or whether they are limited to individual crews.

2.4 Current experience with OPERAS

As part of the OPERAS project, a Utility Steering Group was formed with representatives from Pacific Gas and Electric (PG&E), Northeast Utilities (NU),

Table 2. Instructor observations summary for one crew responding to a simulated accident (input to OPERAS)[a]

Procedure order	Procedure w/problems	Type of problem w/procedure	Skipped step w/problem
E-0	E-0	Application	Step 23
E-1	E-2	Missed step	Step 15
E-2			
E-3			

[a] Scenario: SC02 7:30 AM, Crew: Crew X, Date: 6/6/90.

Wisconsin Public Service, Commonwealth Edison and Niagara Mohawk. Later, other utilities joined the Steering Group, namely Carolina Power and Light, Duke Power and Yankee Atomic. Two of the utilities, PG&E and NU, acted as hosts to demonstrate the use of OPERAS at a PWR simulator and a BWR simulator.

The initial installation at Diablo Canyon was used to collect data on a steam generator tube rupture event and for a licensing issue resolution. Lately, PG&E has used OPERAS for immediate feedback to the crews during simulator training, to provide information to the operations department on procedure concerns that arise during simulator sessions, for

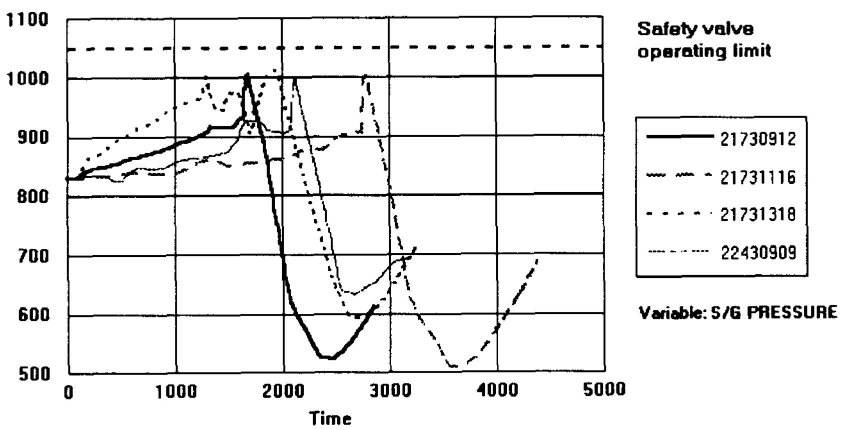

Fig. 3. Plots of a plant variable versus time for four crews.

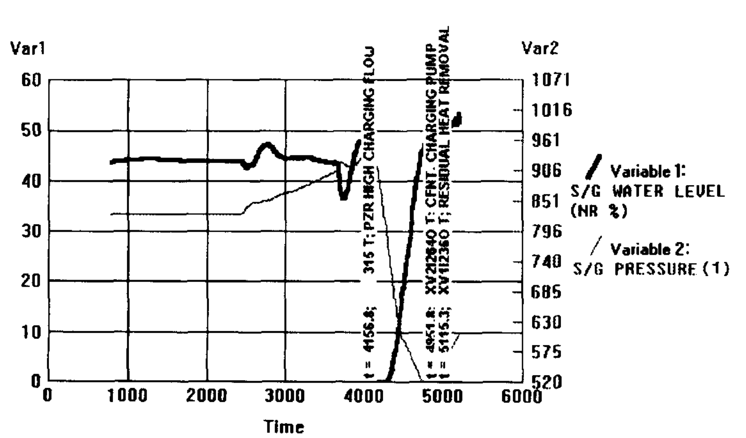

Fig. 4. Variation in steam generator water level and pressure indicating plant malfunctions and operator actions.

investigations into control system improvements, for the resolution of licensing issues and for simulator fidelity purposes.[12]

The installation of OPERAS at the Millstone Unit 1 simulator followed Diablo Canyon. For this installation, a code was written for the plant simulator to collect plant variables and digital data (annunciators, etc.). These data were then written to the simulator's hard disk, and hence to the PC via an RS-232 port. After some initial difficulties, this approach worked quite well and formed the basis of the generic interface for OPERAS. This approach formed the basis of an enhanced system for on-line data collection and analysis as well as post-event analysis. The final version has been installed at Diablo Canyon and tested.

NU, at this time, sees a prime and immediate use of OPERAS as a tool for fidelity checking of the simulators. The tool would be used in two ways: (i) to establish consistency in simulator response, i.e. to show that simulator modifications did not adversely affect the dynamics of the model; and (ii) to use test data from either actual plant transients or comprehensive transient codes to check the fidelity of the modeling in the simulator. NU expects to use OPERAS also for HRA studies in PRAs.

The simulator data collected with OPERAS during a recent series of operator requalification sessions at Diablo Canyon and Millstone Unit 1, were used in conjunction with the ORE data to support revision of a design standard.[13]

2.5 Applications of OPERAS

OPERAS provides the data which can be used for a number of different purposes, such as procedure verification and validation, feedback to crews during simulator scenarios, HRA, determination of the efficacy of human factors improvements to the control boards and the utility of operator aids. Table 3 lists potential uses of OPERAS. Although much thought has been given to the use of OPERAS, the list of uses of the data from OPERAS is probably not complete and awaits further experience of OPERAS by utilities. Below are examples of selected applications of OPERAS.

Table 3. Potential applications of OPERAS

- HRA: time reliability plots and data on potential operator errors to support estimation of their reliability
- Simulator: fidelity aspects, plant responses versus simulator. Simulator data to show stability of simulator programming.
- Procedure validation: confirm procedure achieves desired objectives.
- Identification of incorrect operator responses: due to difficulties with procedures, instruments and controls.
- Crew feedback: accuracy, completeness, timing and sequence of actions, e.g. RHR pump turned off before pump heat-up problems. To examine if there are systematic variations in crew responses. Plant kept within limits of operation.
- Evaluation of human factors changes to control boards.
- Evaluation of operator aids: such as computerized EOP systems.

2.5.1 HRA studies

OPERAS was initially developed as a tool to collect data for HRA studies. This grew out of the need to check the validity of the human cognitive reliability (HCR) model[14] during the ORE project. The HCR/ORE correlation[10] is of prime use in the quantification of time-sensitive HIs in accident sequences in PRAs (see section 3.3.2.1 of Part I of this paper, this issue, pp 27–55). Each HI corresponds to a set of cues observed by the control room crews and acted upon. The times and accuracy of these cues and actions are recorded by OPERAS. The data for different crews are taken together, placed in order, and then plotted in a TRC format.

Another use of simulator data is to see how the crews execute the various tasks. Of interest here is: Do the crews make any errors? Do the crews carry out the same strategy in dealing with the accident? Do the crews have difficulties with the procedures or specific procedural steps? Do they have difficulties with instruments and controls? Also of interest is the percentage of crews that have difficulties. This information and the TRCs are extremely useful to the HRA analysts for estimation of crew non-success probability. An awareness of the crews actual performance can help guide the opinions of experts to form judgements about how the crews might act in actual situations and help them estimate non-success probabilities for inclusion in PRAs.

OPERAS, as part of its input, collects information on observations of the crews' use of procedures, difficulties experienced by the crews with procedures, instruments and controls. These observations are summarized in the form of a database that can be used by plant operations and engineering personnel.

2.5.2 Data collection during training

The work load of the instructors during training sessions are often too high to observe all that is going on. With the addition of OPERAS, the data collection and sorting can be carried out efficiently, thus relieving the instructors of tedious observations. They can then concentrate on team skills rather than having to take time to closely observe specific actions of the crews and record the corresponding response characteristics. OPERAS data, coupled with the video information will be able to inform the trainer when specific actins were taken, by whom and their impact on plant response.

OPERAS offers a good database from simulators on how the plant would be controlled by the control room crews. It also provides information on how closely the crews follow procedures. This information is obtained from instructor observation and from information obtained during post-transient discussions with the crews. This provides a rich source of data for instructors in planning, prioritizing and designing requalification sessions and how they can better help the crews control the plant and reduce the risk of an accident. Summary data obtained by using OPERAS can also be used by the simulator instructors to monitor and document the consistency and variability in crew responses.[15]

2.5.3 Procedure validation

The objective of procedure validation is not only to ensure that the procedure is technically correct but that the control room crew performs the correct action as directed by the procedures. By technically correct, one means that the action(s) specified in the procedure, corresponding to a given plant state, are those that will lead to either the termination or the mitigation of the consequences of the event.

Data collected by OPERAS can be reviewed to assess the impact of procedures and crew actions on plant response. Each of the actions taken by the crews is recorded, along with the time and accuracy of the action. These actions can be examined to see if they are in the correct sequence and if there are any missing or unspecified actions taken by the crew. Figure 4 shows the variation in steam generator water level and pressure as a function of plant malfunctions and operator actions, that can be used for this purpose. Examination of the data can lead on to the conclusions that the plant is controlled as required (or otherwise) and that the crews follow the instructions of the procedures explicitly. A sufficiently large sample of crews should be examined to see if the crews in general can follow the procedures. In addition to the simulator data, data is collected by the instructors on the accuracy and completeness of crews' responses to the event and use of the procedures.

Simulator derived data will show if a wrong action is taken, but input from the observers can show which part of the procedure is causing difficulty. Clearly, if a large number of crews have the same difficulty, there may be a systematic problem with the procedure. For example, an error in the restoration of main feedwater procedure at a PWR plant following a safety injection led 14 to 15 crews in not being able to recover main feed. Subsequently, the utility corrected the procedure and went over the underlying logic to recover main feedwater. Utility staff can select suitable scenarios to test all the procedures over a period of time and prioritize which procedures need to be improved.

3 HUMAN RELIABILITY ANALYSIS (HRA) CALCULATOR

3.1 Introduction

This section describes a HRA calculator jointly sponsored by the EPRI, Texas Utilities (TU Electric) and Accident Prevention Group (APG).[16–18] The HRA calculator is a personal computer (PC)-based software program designed to support analysts performing HRA studies for PRAs, individual plant examinations (IPEs) and continuing plant risk assessments. The calculator provides a menu-driven software for obtaining human reliability estimates using different HRA techniques and documenting the results. The HRA user can be either an experienced HRA practitioner or a beginner.

3.2 Purpose

The HRA calculator is designed for the purpose of quantification of various HIs identified by the HRA analysts. It facilitates the quantification process and it is very useful for performing sensitivity analyses. The code can communicate with PC-based PRA workstations, such as CAFTA,[19] through ASCII data files. The calculator is based mainly on the HRA techniques developed by EPRI over the past decade, as described in Part I of this paper. The calculator is, however, flexible enough to incorporate HRA methods developed by the NRC and other organizations.

3.3 Need for a calculator

In line with the increase in the perceived importance of human reliability in a PRA, has come increased attention given to the quantification of HIs. The HRA practitioners are interested in not only calculating the probabilities of the HIs, but also in examining the impact of various influence factors, such as quality of procedures and training, on the estimated probabilities. Also of interest is the examination of alternative models to see how the selection of models can affect the probabilities.

Documentation of the assumptions which lead to the calculated HI probabilities need to be recorded, along with the model parameters and results. There is also a need to transfer the HI data to the PRA workstation so as to minimize transposition errors. Thus, there is a need for a human reliability calculator which combines a number of HRA calculational techniques that would allow the user to select the most appropriate HRA model, carry out sensitivity studies and document the results.

3.4 Basic requirements

The HRA calculator is mainly designed for quantification of various HIs identified by the HRA analysts. It is based on the HRA techniques developed by EPRI and APG for TU Electric during their IPE study. The following basic requirements were identified for the calculator to fulfil the project objectives.

- Perform HRA quantification efficiently and systematically
- Perform sensitivity studies easily
- Check assumptions and results easily
- Document results (report quality outputs)

Furthermore, the code should be user friendly and capable of easily transferring data to PRA workstations. It should also be easily expandable to include other HRA quantification methods (e.g. NRC-sponsored methods).

3.5 Design

The approach to the design of the calculator is to use a higher level applications program (e.g. Microsoft Excel™) operating in a Windows™ environment. The approach was taken to base the software package on an industry standard, which would have the benefit of being user friendly. By using this approach, the prototype was also put together relatively quickly. Communication with PC-based systems analysis programs is accomplished by ASCII data transfers. The ASCII files are defined according to the requirement of the user.

The software tool presents to the user various options via menus. The Windows™ design leads the user through the options to required calculation(s). The user can also choose to carry out sensitivity studies or carry out comparative analyses. On completion of a calculation, the user can request a record of the calculation. The record covers the input data, the estimated human error probability and probability plots as appropriate. These data supply the user with records to be used in IPE/PRA calculation files.

3.6 Flowchart and HRA modules

HRA studies normally address three types of HIs that are included in the PRA logic models. These are: pre-initiating event HIs (or type A), human errors causing an initiating event (or type B), and post-initiating event HIs (or type C). Type C HIs are further divided into two categories: type CP, procedure driven HIs following a plant transient or accident, and type CR, recovery actions. Type A and C HIs are sometimes referred to as latent and dynamic human interactions in PRAs. The effect of type B events are normally implicit in the initiating event frequencies obtained from plant operating experience. Consequently, this type has not been included in the HRA calculator at this time.

The organization of the HI quantification methods is arranged in an hierarchical manner (see Fig. 5). The HRA calculator covers the screening analysis of both latent (type A) and dynamic (type C) HIs, as well as detailed quantification of type CP and CR HIs. The detailed HRA calculator flowchart showing its various quantification methods can be found in Ref. 16. The logic underlying the hierarchical structure can be changed to reflect the addition of other HRA methods as the state-of-the-art in HRA modeling changes.

Different techniques for obtaining human reliability estimates are provided in the HRA calculator, depending on the availability of plant-specific data (e.g. simulator data), importance of the HI and the scope of the study. For example, a method for quantification of time-sensitive procedure-driven operator actions following a plant transient is use of plant-specific TRCs. By selecting this option, the HRA analyst has to input a reasonable number (five or more) of operating crew response time data points for each HI and an estimate of the time available to perform the action. The HRA calculator develops the TRC and the best lognormal fit to the input data and also calculates the non-response probability for the given time window. Figure 6 shows an illustrative plant-specific TRC with crew response times of 25, 15, 29, 141, 63 and 174 s. The non-response probability estimate (p_2) is 0·08 for a time-sensitive action with a time window of 200 s. Generic HCR/ORE correlations derived from the ORE database are also provided in the HRA calculator as another option.[20]

3.7 Potential future extensions/developments

3.7.1 Potential near-term extensions

During the programming and testing of the decision trees used for the estimation of cognitive error probability (p_1), it was realized that they were relatively inflexible. To apply such decision trees in practice, users need to be able to change both the structure and the end-point estimates. Near-term extensions to the HRA calculator could be to program a flexible decision tree routine that would allow the HRA analysts to either modify the existing pre-defined decision trees or generate their own trees based on their own influence factors. (The reader is referred to Part I for a discussion of decision trees in this context.) (this issue, pp 27–55)

3.7.2 The NRC sponsored methods

There are a number of published NRC-sponsored HRA methods which have been used in both generic and plant-specific PRA and IPE studies for nuclear

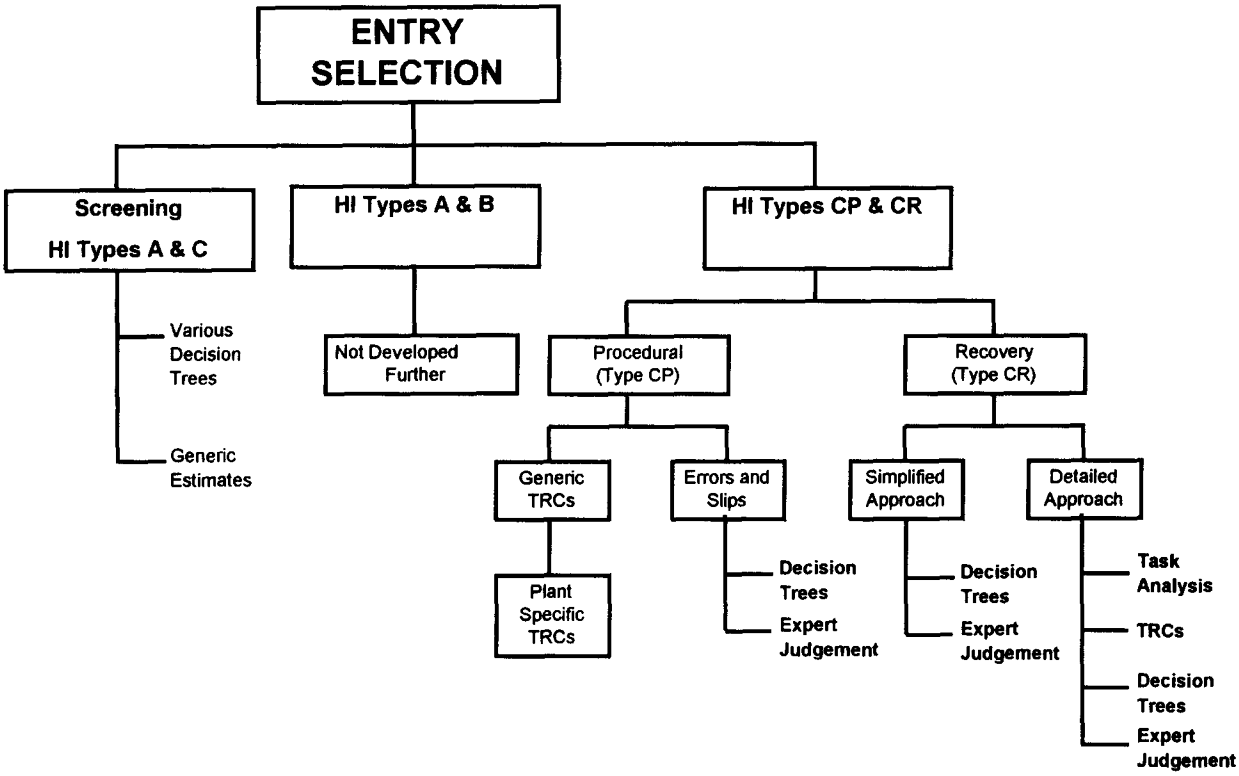

Fig. 5. Schematic arrangement of HRA calculator modules.[18]

power plants. A review of the HRA methods can be found in Haney *et al.*[21] These methods can be grouped into two main categories:

(1) Methods in the HRA Handbook[22] and the *Accident Sequence Evaluation Program (ASEP) HRA procedure*[23]
(2) Expert judgement-based methods

Examples of the HRA methods developed by Swain are the technique for human error rate prediction (THERP), including a dependency model and a generic TRC for estimation of cognitive errors.[22,23] THERP could be used for analysis of type A HIs (or latent errors). The expert judgement-based methods cover both structured methods such as success likelihood index method/multi-attribute utility decomposition (SLIM/MAUD)[24] and more direct expert estimation methods.[25,26] The direct judgement estima-

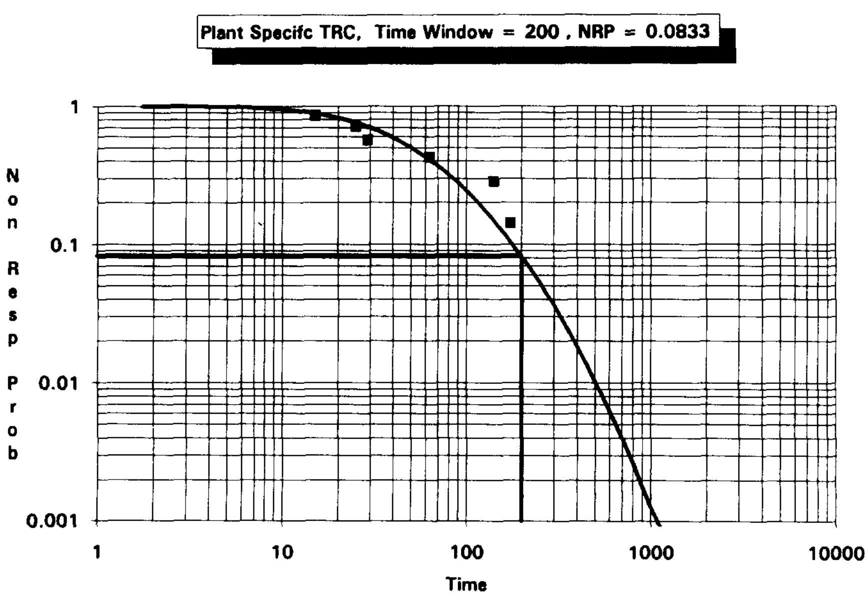

Fig. 6. Typical plant-specific TRC generated by the HRA calculator.

tion methods (e.g. the direct numerical estimation technique) can be included in the HRA calculator to supplement its existing methods.

3.7.3 Potential future enhancements

A shortcoming of current HRA models is the treatment of dependencies. Dependencies are a significant contributor to overall risk and need to be modelled in a consistent manner. A discussion on the various types of human dependencies with some recommendations on their treatment, is covered in the SHARP1 document.[27] In it, human interaction dependencies are grouped into four classes, as follows:

- Class 1 Dependence of type C HIs on the scenario.
- Class 2 Dependence between multiple HIs in the same scenario (primarily types B and C).
- Class 3 Dependence between multiple HIs within the same system (primarily types A and B).
- Class 4 Dependencies within the HI quantitative models for human interactions.

Some dependencies in the context of the HCR and HCR/ORE correlations (class 1 and class 2) are discussed in section 3 in Part I of this paper, with some recommendations for their treatment. Swain and Guttmann[22] have proposed a model of dependencies between human operators which could be used for class 3 and class 4 dependencies. However, more work needs to be undertaken on this whole subject.

Another area for future development is the treatment of uncertainties and incorporation of modules in the software to address this issue. It is noted that the HCR/ORE correlations provide uncertainty bounds which have already been included in the HRA calculator. However, more work is required to address uncertainties associated with other methods and estimates.

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REFERENCES

1. Joschek, H. I., Risk assessment in the chemical industry. In *Proceedings of the ANS/ENS Topical Meeting on Probabilistic Risk Assessment.* American Nuclear Society, La Grange Park, IL, USA, 1981.
2. Topmiller, D. A., Eckel, J. S. & Kozinsky, E. J., *Human Reliabiilty Data Bank for Nuclear Power Plant Operations* (NUREG/CR-2744, Vol. 1). US Nuclear Regulatory Commission, Washington, DC, USA, 1982.
3. Minarick, J. W. & Kukielka, C. A., *Precursors to Potential Severe Core Damage Accidents*: 1969–1979, *A Status Report* (NUREG/CR-2497, Vols 1 and 2). US Nuclear Regulatory Commission, Washington, DC, USA, 1982.
4. Trager, Jr, T. A., *Case Study Report on Loss of Safety System Function Events* (AEOD/C504). US Nuclear Regulatory Commission, Washington, DC, USA, 1985.
5. Reason, J., *Human Error.* Cambridge University Press, New York, USA, 1990.
6. Dougherty, E. M., HRA—where shouldst thou turn? *Reliability Engng and System Safety,* **29** (3) (1990) 283–99.
7. Spurgin, A. J., Moieni, P. & Luna, C. J., The current status of the use of PCs in human reliability analysis. *Reliability Engng and System Safety,* **30** (1990) 51–64.
8. Spurgin, A. J. *et al.*, Design and use of an operator reliability assessment system connected to power plant simulators. In *Proceedings of* 1991 *International Conference on Power Plant and Power System Training Simulators and Modeling,* Electric Power Research Institute, Palo Alto, CA, USA, 1991.
9. Spurgin, A. J., Hallam, J. W. & Spurgin, J. P., *Operator Reliability Assessment System (OPERAS), Vols* 1, 2 *and* 3 (EPRI RP-3082-1). Electric Power Research Institute, Palo Alto, CA, USA, 1992.
10. Spurgin, A. J. *et al.*, *Operator Reliability Experiments Using Power Plant Simulators, Vols* 1 *and* 2: *Executive Summary and Technical Report* (EPRI NP-6937). Electric Power Research Institute, Palo Alto, CA, USA, 1990.
11. Spurgin, A. J. *et al.*, *Operator Reliability Experiments Using Power Plant Simulators, Vol.* 3: *Appendices* (EPRI NP-6937L). Electric Power Research Institute, Palo Alto, CA, USA, 1991.
12. Welsch, J. & Sawyer, L., Automatic monitoring of control-room crews during simulator sessions for training improvements. In *Proceedings of the* 1992 *SCS Eastern Simulation MultiConference of the International Simulators Conference,* The Society for Computer Simulation, San Diego, CA, USA, 1992.
13. Moieni, P., Spurgin, A. J. & Spurgin, J. P., Use of simulator data on operators time response to support revision of a design standard., *Proceedings of the* 1992 *IEEE Fifth Conference on Human Factors and Power Plants,* Institute of Electrical and Electronics Engineers, New York, USA, 1992.
14. Hannaman, G. W., Spurgin, A. J. & Lukic, Y. D., *Human Cognitive Reliability Model for PRA Analysis* (EPRI RP 2170-3). Electric Power Research Institute, Palo Alto, CA, USA, 1984.
15. Spurgin, A. J., Moieni, P. & Orvis, D. D., Some thoughts on the use of data for assessing training effectiveness. In *Proceedings of the* 1993 *SCS Simulation MultiConference,* The Society for Computer Simulation, San Diego, CA, USA, 1993.
16. Moieni, P., Spurgin, A. J. & Spurgin, J. P., *Human Reliability Analysis (HRA) Calculator, Vol.* 1:

Technical Description, (EPRI RP-3082-03, Draft Report). Electric Power Research Institute, Palo Alto, CA, USA, 1992.
17. Spurgin, A. J., Moieni, P. & Spurgin, J. P., *Human Reliability Analysis (HRA) Calculator, Vol.* 2: *User's Manual* (EPRI RP-3082-03, Draft Report). Electric Power Research Institute, Palo Alto, CA, USA, 1991.
18. Moieni, P. *et al.,* A PC-based human reliability analysis (HRA) calculator. In *Proceedings of PSA '93, International Topical Meeting on Probabilistic Safety Assessment,* American Nuclear Society, La Grange Park, IL, USA, 1993.
19. Science Applications International Corporation, *CAFTA: A Fault Tree Development Work Station,* Los Altos, CA, USA, 1989.
20. Spurgin, A. J., Moieni, P. & Parry, G. W., *A Human Reliability Analysis Approach Using Measurements for Individual Plant Examination* (EPRI NP-6560L). Electric Power Research Institute, Palo Alto, CA, USA, 1989.
21. Haney, L. N. *et al., Comparison and Application of Quantitative Human Reliability Analysis Methods for the Risk Methods Integration and Evaluation Program (RMIEP)* (NUREG/CR-4835). US Nuclear Regulatory Commission, Washington, DC, USA, 1989.
22. Swain, A. D. & Guttmann, H.E., *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applicaions* (NUREG/CR-1278). US Nuclear Regulatory Commission, Washington, DC, USA, 1983.
23. Swain, A. D., *Accident Sequence Evaluation Program Human Reliability Analysis Procedure* (NUREG/CR-4772). US Nuclear Regulatory Commission, Washington, DC, USA, 1987.
24. Embrey, D. E., SLIM/MAUD—A computer based technique for human reliability assessment. In *Proceedings of ANS/ENS Topical Meeting on Probabilistic Safety Methods and Applications,* Electric Power Research Institute, Palo Alto, CA, USA, 1985.
25. Comer, M. K. *et al., Generating Human Reliability Estimates Using Expert Judgement, Main Report, Vols* 1 *and* 2 (NUREG/CR-3688). US Nuclear Regulatory Commission, Washington, DC, USA, 1984.
26. Meyer, M. A. & Booker, J. M., *Eliciting and Analyzing Expert Judgement* (NUREG/CR-5424). US Nuclear Regulatory Commission, Washington, DC, USA, 1990.
27. Wakefield, D. J. *et al., Systematic Human Action Reliability Procedure (SHARP) Enhancement Project—SHARP1 Methodology Report* (EPRI TR-101711). Electric Power Research Institute, Palo Alto, CA, USA, 1992.