HUMAN RELIABILITY: AN EVALUATION OF ITS UNDERSTANDING AND PREDICTION

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INTRODUCTION

This paper presents a viewpoint on the state-of-the-art in human reliability. The bases for this viewpoint are, by and large, research projects conducted by the NUS for the Electric Power Research Institute (EPRI) primarily with the objective of further enhancing the credibility of PRA methodology. The presentation is divided into the following key sections: Background and Overview, Methodology and Data Base with emphasis on the simulator data base.

BACKGROUND AND OVERVIEW

Impact of Human Interactions

A comprehensive treatment of human interactions is deemed to be a key to the adequate understanding of various accident sequences and their relative importance in public safety considerations. There is an abundance of evidence to support the notion that humans play a dominant role in both causing and terminating accidents at various industrial facilities. Such evidence comes in the form of actuarial data (e.g., Chernobyl, TMI-2, numerous precursors) or predictions from various generic and plant-specific PRA (Probabilistic Risk Assessment) studies. For the purposes of illustration, Table 1 provides several examples of adverse human interactions while Table 2 provides examples of beneficial human actions. Less widely understood and publicized is beneficial human impact in preventing and mitigating various accident sequences, as well as recovering the plant from near-catastrophic accident scenarios. Some early, well-publicized PRA studies,[1] have focused primarily on the testing and maintenance actions prior to the initiating event and thus a perception was created that, given the initiator, nuclear safety almost entirely relied on the engineering design. Important decisions in the control room and numerous interactions during complex accident sequences were treated superficially. As a result, the human contribution was seen as primarily negative. This in turn, created skepticism in usefulness and realism of PRAs among the plant operators and many utility managers. Some more recent PRA studies recognized this beneficial impact and attempted modestly to account for it.

Balance

Intuitively, one can argue that adverse and beneficial human impacts ought to balance out unless there are some compelling reasons why a mismatch should exist. One can hypothesize that an example of a mismatch could be a plant design philosophy and/or a regulatory interference which resulted in a restrictive operating band and, thus, presented inherent difficulties to operate the plant within appropriate safety margins. Another possible cause of a mismatch could be an effect of the plant management practices, an organizational structure or management/labor relations which are reflected throughout the organization, filtering down to the levels of plant operating and maintenance crews and perhaps being manifested in an inadequate plant performance.

The above discussion leads to a notion that for a well-designed and managed plant, the balance between the adverse and beneficial human impact is achievable. For such a plant, there is no reason whatsoever why the safety objective on severe core damage frequency of 10^{-5} per year or perhaps even 10^{-6} could not be met; as some regulatory authorities in Europe, in particular, are demanding.

Human Reliability Discipline

A discipline of human reliability is capable of addressing this fundamental issue of evaluating whether a balance does exist and, if not, what it takes to remedy imbalances. Remedies could take the form of say:

- Simplifying and streamlining man-machine interface;
- Enhancement of operator training to encompass for relatively low probability scenarios;
- Plant backfitting as a last resort.

TABLE 1. EXAMPLES OF ADVERSE HUMAN INTERACTIONS

SOURCE	METHOD	HUMAN IMPACT	REFERENCES
WASH-1400 1975	POST-EXAMINATION OF FAULT TREES	50-80% CONTRIBUTOR TO SAFETY SYSTEM FAILURES	M. TAYLOR TESTIMONY TO LEWIS COMMITTEE
AIPA STUDY 1978	POST-EXAMINATION OF ACCIDENT SEQUENCES	~50% CORE HEAT UP CONTRIBUTION	ANS TRANSACTIONS, VOL. 33, SAN FRANCISCO, 1979
DRS STUDY 1979	EVALUATION OF DOMINANT SEQUENCES (CONTAINED IN THE REPORT)	63% CORE MELT FREQUENCY CONTRIBUTOR	EPRI REPORT N-180NR
TMI 1979	ACTUARIAL	MAJOR CONTRIBUTOR	KEMENY COMMISSION REPORT
GERMAN CHEMICAL INDUSTRY - 1981	ACTUARIAL	80-90% OF ALL INCIDENTS IN CHEMICAL INDUSTRY	JOSCHEK, PORT CHESTER PRA CONFERENCE
RINGHALS #2 1983	EVALUATION OF DOMINANT SEQUENCES (CONTAINED IN THE REPORT)	77% CORE MELT FREQUENCY CONTRIBUTOR	RINGHALS PRA — SWEDISH STATE POWER BOARD
EPRI FIVE STUDY REVIEW 1983	POST-EXAMINATION OF ACCIDENT SEQUENCES	10% (ANO)-87% (BRP) CORE MELT FREQUENCY CONTRIBUTOR	EPRI NP-3265
GENERAL AVIATION 1985	ACTUARIAL	87% ATTRIBUTABLE TO PILOT ERRORS	L.A. TIMES, MARCH 1986
FRENCH EXPERIENCE FROM 29 UNITS, 1986	ACTUARIAL POST-TRIP EXAMINATION	59% CONTRIBUTOR TO 130 SCRAMS	P. TANGUY, SAN DIEGO THERMAL REACTOR SAFETY CONFERENCE PAPER
CHERNOBYL 1986	ACTUARIAL	MAJOR CONTRIBUTOR	SOVIET VIENNA REPORT

TABLE 2. EXAMPLES OF BENEFICIAL HUMAN ACTIONS

1976	BROWNS FERRY FIRE
1977	BEZNAU CLOSURE OF BLOCK VALVE
1978	RANCHO SECO LIGHT BULB INCIDENT
1979	DOEL-2 STEAM GENERATOR TUBE RUPTURE
1980	CRYSTAL RIVER 3 — INSTRUMENTATION AND CONTROL MALFUNCTION
1980	ST. LUCIE #1 NATURAL CIRCULATION COOLDOWN
1980	HATCH LOSS OF HIGH PRESSURE COOLING
1980;1983	BROWNS FERRY AND SALEM CONTROL ROD TRIP FAILURES
1982	GINNA STEAM GENERATOR TUBE RUPTURE
1983	EPRI NP-3265
1985	DAVIS-BESSE TOTAL LOSS OF FEEDWATER
1986	NINE UNIT FRENCH BLACKOUT
1986	NUS-4900; FACTOR OF 6 -12 ON SCDF
1986	NUS-4954; CAORSO PRA — FACTOR OF 30 ON SCDF

Human reliability should not be confused with so-called human factors discipline which was born in the nuclear industry in the aftermath of the TMI accident. It existed prior to that in the aircraft and aerospace industries. This discipline could be viewed primarily as a design tool which focuses on improvement of the environment in which the plant operating crew functions, e.g., man-machine interface in the control room, quality of procedures, communications, job/task analysis, etc. Human reliability is an assessment tool which evaluates quantitatively effectiveness of these measures arising from the human factor considerations.

METHODOLOGY

Human behavior is a complex subject that does not lend itself to relatively straightforward models like those for component and system reliability assessments. In order for this complexity to be amenable to modeling, the first step is to classify human interactions into a limited number of classes. The second step is to introduce an acceptable framework to organize a study. The third step is to select a range of suitable models (or correlations), having accomplished the above, one needs to develop a credible data base. Hence, the essential ingredients of the human reliability assessment are classification, framework, selection of quantification methods and data base formulation.

Classification

In the EPRI-sponsored intercomparison of five early large scale PRA studies,[2] it was found that PRA studies treated five types of human interactions (see Table 3). These types of human interactions are distinguishable by the approach and data used for incorporating them into the PRA studies, although some may not be too different regarding behavioral characteristics, e.g., Types 3 and 5. Such, or an equivalent classification, is required to address a wide spectrum of human interactions. It should be added that Chernobyl accident taught us that the plant personnel can also advertently disable the equipment.

Framework

The EPRI-sponsored SHARP project[3] developed a systematic analysis framework to aid PRA analysts in selecting the approach and quantification technique for incorporating the different types of human interactions, such as those listed above, into the PRA studies. Such a framework was not intended to prescribe a particular method of human reliability analysis; but rather to stimulate systems and human reliability analysts to incorporate good engineering judgment and to state their assumptions more explicitly in a scrutable manner. The framework developed consisted of seven steps (see Table 4) with defined objectives and linkages to the accident sequence development/systems analysis elements of a PRA study. This framework was amplified by defining alternative activities and rules for the analysts to consider in performing each of the seven steps. The purpose of the activities and rules is to help the analysts organize their approach and state their rationale and assumptions for selecting the approach, model or data.

Quantification Methods

An examination of current library of PRA studies identified different ways that analysts have quantified human interactions in the past. Figure 1, expanded from EPRI NP-3583, depicts these pathways in a diagrammatic form. Table 5, on the other hand, illustrates a link between human interaction types summarized in Table 3 and a possible implementation of the SHARP steps presented in Table 4.

In the quantification process, it is essential to use mathematical relationships that enable the user to predict time-dependent human response probability in terms of key engineering and operation parameters such as type of behavior, available response time and performance shaping factors such as stress, experience, quality of man-machine interface. The examples are HCR (human cognitive reliability) correlation[4] and CSE (cognitive sub-event) model.[5] Whereas HCR is an integral correlation of plant personnel non-response probability, the CSE represents an account of some intervening variables. The HCR correlation is discussed briefly below.

HCR Correlation

While developing SHARP, a need was identified to attempt to define a model or correlation for helping PRA analysts quantify the reliability of control room crew responses to accident sequences. The correlation should be realistic, systematic and repeatable when applied by different analysts. Additionally, it should be sensitive to the effects of task time, available plant time windows, crew stress, man-machine interface, etc.

Such a correlation named HCR (Human Cognitive Reliability) has been developed by NUS and provides the time dependent human non-response probability in terms of key engineering and operational input parameters. These parameters are:

a. Three types of human "cognitive" behavior: skill-, rule-, and knowledge-based behavior stemming from those defined by Jens Rasmussen.[6]

b. Median response time of the crew ongoing a specific task, based upon estimates made by experts or from measurements of actual or simulated events.

c. Performance-shaping factors (PSFs) such as stress, experience, and quality of information from man-machine interfaces evaluated by expert judgment or from small scale tests.

Table 3

Classification of Human Interactions per EPRI NP-3265

1. Testing and maintenance actions prior to an initiating event; plant personnel can compromise equipment availability by inadvertently disabling it during normal or shutdown operation. Include errors in calibration, testing, routine system operations and maintenance that result in equipment unavailability when demanded by the initiator. They are typically incorporated into the fault trees. The most important errors are typically miscalibration of common instruments and incorrect positioning of valves during testing and maintenance.

2. Actions might cause initiating events. By committing some error, the plant personnel initiate an accident sequence. Contribution of these errors typically appears in the initiating event frequency either implicitly or explicitly.

3. Actions taken to ameliorate various accident scenarios by virtue of following emergency procedures. Involve success and failures paths in following emergency operating procedures or rules known to the control room operators. They are incorporated explicitly into the logic structures (e.g., event and fault trees, Boolean expressions); typically in the event trees.

4. Actions which exacerbate or fail to terminate various accident scenarios in attempting to follow procedures. The plant personnel, in attempting to follow the emergency procedures, can make a mistake that aggravates the accident sequence or fails to terminate an accident sequence. They are typically incorporated into the event trees.

5. Recovery actions, by improvising plant personnel can restore and operate initially unavailable or failed equipment to terminate an accident sequence. By improvising, the plant personnel can restore and operate virtually unavailable, failed or isolated equipment to terminate an accident sequence. They include recovering offsite power, repairing diesel generators, restoring chilled water system, venting the containment, operator actions in seismic, flooding events, etc. They are typically incorporated into the event trees.

Table 4

Brief Summary of SHARP Steps

1. Definition. To ensure that all different types of human interactions are adequately accounted for in the construction of logic diagrams (e.g., event and fault trees, GO diagrams or Boolean expressions).

2. Screening. To identify the key human interactions that are significant for the public safety considerations.

3. Breakdown. To amplify a qualitative description of important human interactions identified in Step 2 by defining the key influence factors necessary. For modeling purposes, it is accomplished by virtue of breaking down descriptions into tasks and subtasks.

4. Representation. To identify and select most appropriate techniques for modeling important human interactions in logic structures.

5. Impact Assessment or Integration. To explore the impact of significant human actions identified in the preceding step on the system logic trees.

6. Quantification. To apply appropriate data or other quantification methods to assign probabilities for the various interactions examined, determine sensitivities, and establish uncertainty ranges.

7. Documentation. To include all necessary information for the assessment to be traceable, understandable, and reproducible.

Table 5

RELATIONSHIP BETWEEN CLASSIFICATION TYPES AND SHARP STEPS

HUMAN INTERACTIONS — CLASSIFICATION TYPES		SHARP STEPS			
NO.	DESCRIPTION	SCREENING STEP 2	REPRESENTATION STEP 4	INTEGRATION STEP 5	QUANTIFICATION STEP 6
1	Maintenance and test	Qualitative or	HRA tree	Fault trees	THERP Data Base (NUREG/CR-1278 Table 20-XX)
2	Accident initiation	quantitative	LIKE ANY OTHER INITIATOR		
3	Procedure following, including decision-making	method —	OAT/HRA tree	Event/fault trees	HCR/NUREG/CR-1278
4	Aggravation of accident sequences	e.g., Appendix A	OAT/HRA tree	Event/fault trees	Expert judgment, e.g., confusion matrix
5	Recovery improvizations in accident management sequences	EPRI NP-3583	OAT/HRA tree	Event trees	HCR/NUREG/CR-1278

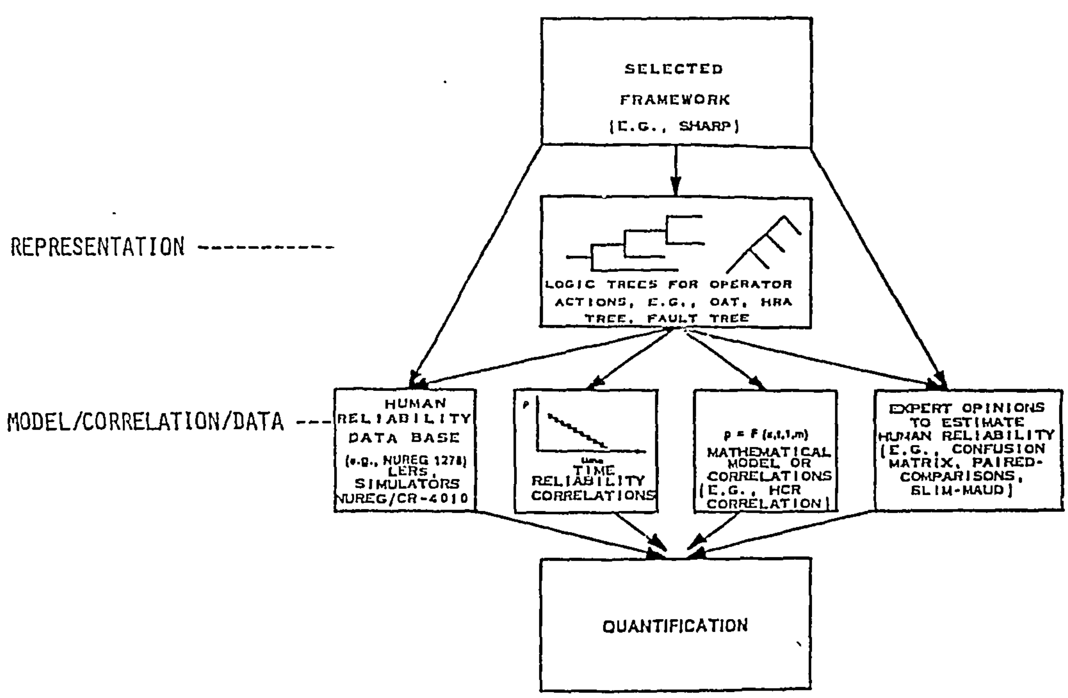

Fig. 1. Pathways for Quantification of Human Interactions

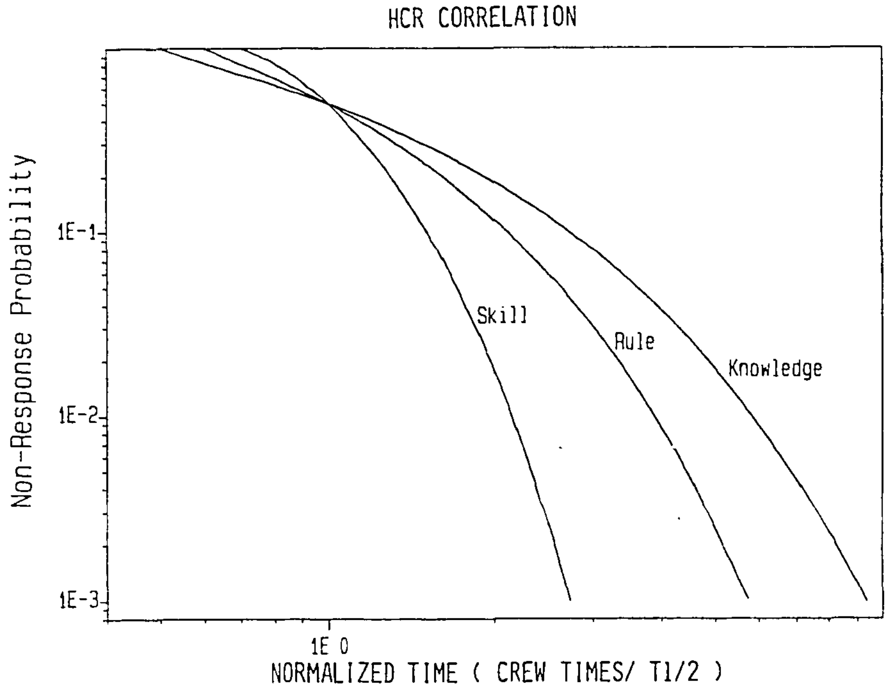

Fig. 2. Normalized Crew Non-Response Curves for Skill-, Rule-, Knowledge-based Cognitive Processing

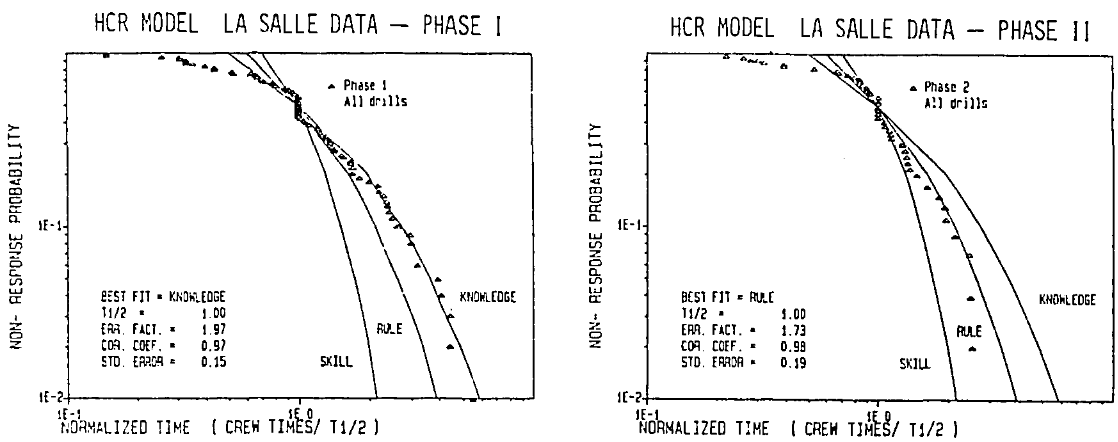

Fig. 3. La Salle Test Aggregate Responses of Operators for Phases I and II

The essence of the HCR correlation is a normalized time-reliability curve whose shape is determined by the dominant human cognitive processing associated with the task being performed. The normalized curves of Figure 2 correspond to the three types of cognitive processing identified by Rasmussen. The normalized time is the actual time divided by the median time ($T_{1/2}$) taken by crews to perform a given task. The median time has, at this time, to be obtained from simulator measurements, task analyses or expert judgment. The effect on crew performance of operationally-induced stress, control room equipment arrangement, etc., are accounted for by modification of the median time to perform the task. A simplification is that the type of cognitive processing is unaffected by the above factors while the time to perform the task is affected.

DATA BASE

Includes a data base from which the analysts can extract parameters for quantifying specific human interactions. A data base may include plant-specific experience from available records or generic experience from, say, licensee event reports. It may include plant simulator data which are extremely useful in particular, for rare events. If none of the above is available, as a last resort expert judgment represents an acceptable alternative. The prime example of a data base is Chapter 20 of the Handbook[7] which is used typically in conjunction with HRA trees.

Simulator Data

The modern control room training simulators provide a potential for making measurements of operator performance to improve understanding of the basic models and provide support for human reliability estimates. Simulator data of crew responses to repeated events and some small scale tests were utilized to illustrate the initial calibration of the HCR correlation coefficients for different types of cognitive processing since the available data were sparse.

Recognizing a fundamental lack of data for the wide variety of scenarios scrutinized in a PRA, data from the most realistic conditions are needed to support the development of human reliability data suitable for safety assessments. Measurements of operating crew performances are being taken starting with the La Salle simulator tests.[8] These tests indicate that using models such as HCR to classify and organize measurements is a valuable tool for understanding the contribution of control room decision-making and actions to plant safety. Furthermore, such measurements benefit the training program by helping to identify specific areas for trainers (instructors) to address with plant crews such as types of communications, organization of crew decisions, and identifying the maturing of experienced crews.

Figure 3 summarizes the La Salle tests, which have been conducted in two phases, via aggregate responses of the operators. The trend of the response times has moved from knowledge-based to rule-based. This is attributable to the training program. Phase I tests were conducted shortly after the operators were faced with the symptom-based procedures. Phase II tests were conducted eight months later and may reflect cumulative training in these procedures.

The current program is currently focusing on large scale plant simulator experiments. The key objectives are 1) to obtain quantitative performance data on operator responses in the control room for a number of potential accident sequences at nuclear power plants by using full scale plant simulators, and 2) to develop or refine models to be validated by the data, for the purpose of extrapolating the data to a wider range of circumstances than those under which it was obtained.

The program is currently split into two phases. The first phase (October 1986 to October 1987) is focused on data based extensions and validations of the HCR (Human Cognitive Reliability) Correlation and CSE (Cognitive Sub-Event) model. The second phase (October 1987 to March 1989) constitutes an expanded experimental program which will include on the order of 200 simulator tests.

Currently, six U.S. utilities: Commonwealth Edison (La Salle - BWR), Pacific Gas and Electric (Diablo Canyon - PWR), Northeast Utilities (Millstone 2 -PWR), Wisconsin Public Service (Kewaunee - PWR), Philadelphia Electric (Limerick - BWR), Pennsylvania Power and Light (Susquehanna - BWR), and Electricité de France (EdF) are participating in the program.

The U.S. participants typically: a) make the full scale plant simulators and the associated equipment together with the operating crews available for the conduct of experiments; b) have close involvement in defining test scenarios; c) assist in observations and d) share the information and insights to be generated from data comparisons. Between the sponsor, contractor, subcontractor (General Physics) and the participating utilities enormous resources are invested into this project.

At the time of writing this paper, five week series of tests at Diablo Canyon has been completed, five week series at Susquehanna is in progress, a new series at Diablo Canyon initiated and the planning is being done for the Limerick tests.

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