ELSEVIER

PII: S0951-8320(97)00081-1

Reliability Engineering and System Safety 58 (1997) 249–274

0951-8320/97/$17.00

Human-centered modeling in human reliability analysis: some trends based on case studies

F. Mosneron-Dupin*[a], B. Reer[b], G. Heslinga[c], O. Sträter[d], V. Gerdes[c], G. Saliou[a] & W. Ullwer[b]

[a]*EDF/DER/ESF, 1 avenue du Général de Gaulle, 92141 Clamart, France*
[b]*Forschungszentrum Jülich, 52425 Jülich, Germany*
[c]*N.V. KEMA, P.O. Box 9035, 6800 ET, Arnhem, The Netherlands*
[d]*GRS, Dept. 501, Forschungsgelände, 85748Garching, Germany*

(Received 18 January 1997; accepted 30 June 1997)

As an informal working group of researchers from France, Germany and The Netherlands created in 1993, the EARTH association is investigating significant subjects in the field of human reliability analysis (HRA). Our initial review of cases from nuclear operating experience showed that decision-based unrequired actions (DUA) contribute to risk significantly on the one hand. On the other hand, our evaluation of current HRA methods showed that these methods do not cover such actions adequately. Especially, practice-oriented guidelines for their predictive identification are lacking. We assumed that a basic cause for such difficulties was that these methods actually use a limited representation of the stimulus–organism–response (SOR) paradigm. We proposed a human-centered model, which better highlights the active role of the operators and the importance of their culture, attitudes and goals. This orientation was encouraged by our review of current HRA research activities. We therefore decided to envisage progress by identifying cognitive tendencies in the context of operating and simulator experience. For this purpose, advanced approaches for retrospective event analysis were discussed. Some orientations for improvements were proposed. By analyzing cases, various cognitive tendencies were identified, together with useful information about their context. Some of them match psychological findings already published in the literature, some of them are not covered adequately by the literature that we reviewed. Finally, this exploratory study shows that contextual and case-illustrated findings about cognitive tendencies provide useful help for the predictive identification of DUA in HRA. More research should be carried out to complement our findings and elaborate more detailed and systematic guidelines for using them in HRA studies. © 1998 Elsevier Science Limited.

1 INTRODUCTION

This article presents the work of the European Association on Reliability Techniques for Humans (EARTH), an informal working group created in 1993 by Electricité de France (EDF), Gesellschaft für Anlagen und Reaktorsicherheit mbH (GRS, Germany), N.V. KEMA, (The Netherlands) and Forschungszentrum Jülich (Germany).

Human reliability analysis (HRA) is widely recognized as a weak point of probabilistic safety assessment (PSA). However, to renounce HRA would significantly reduce the benefits gained from PSA, since man–machine interaction is an essential factor in risk and safety. Moreover, safety assessment is a necessity for systems involving risk. Thus, if no sufficient confidence can be put in HRA, designers will have to replace human actions by automatic actions (which are easier to assess), even when this is not optimal for operation (due to complexity, cost, spurious actuations, etc.).

Therefore, there is a need to make progress with HRA methods. Progress is particularly necessary with respect to:

- *extraneous actions* ('introduction of some task or step that should not have been performed' [1]);
- *errors of intention* ('operator intends to perform

---

*Present address: EDF CNPE, BP15, 68740 Fessenheim, France.

> some action that is incorrect but that he believes to be correct or to represent a superior method of performance' [1]).

Such types of errors are hardly dealt with in today's PSA studies. Yet their importance is likely to grow in new systems. Since these systems are increasingly automated, the role of the operator becomes one of a supervisor, involving complex cognitive processes. The risk is then no longer just one of omission of simple actions—which are controlled by the machine—but more that of performance of extraneous actions decided by the operator to deal with a real or supposed limit of the automated system.

For all these reasons, in 1993 it was decided to create the EARTH group, which brings together specialists from EDF, GRS, KEMA and Forschungszentrum Jülich (Jülich Research Center). The main objective of EARTH is to contribute to the improvement of HRA methods at a European level by:

- gradually bringing the points of view, methods and programmes of various European partners closer together;
- focusing exchanges on the problems involved in taking account of errors of intention and extraneous actions.

Scheduled meetings (about two per year) set the framework of the group's working methods. Such meetings are held for:

- reviewing the status of the various partners' work on the subject;
- defining certain common tasks on which each entity works within its own programmes.

Sections 2–4 of this article present the programme carried through to date. The work began with a bibliographical investigation (Section 2) of the questions of extraneous action and error of intention. This investigation confirmed that it would be useful:

- to go back to cases of real and simulated events;
- to investigate the potential uses of the concept of 'cognitive tendency' in HRA.

Ideas, approaches and preliminary results about the latter two items are presented in Section 3 (Event Analysis) and Section 4 (Cognitive Tendencies). Finally, Section 5 (Conclusions) outlines current prospects.

2 LITERATURE REVIEW

2.1 Introduction of cases and definition of subject

The main focus of EARTH's investigations on HRA progress concerns a type of *extraneous action*, that is based on an *error of intention*, and that results in an *unsafe intervention*, i.e. adverse change of system state by an active human input.

For simplification, such a type of action will be designated as *d*ecision-based *u*nrequired *a*ction (DUA). The term 'unrequired' often characterizes a situation in which no human intervention is needed to avoid a certain system failure: the system conditions are intrinsically safe or stable, and relevant system functions are working within their limits of tolerance or are in proper standby state. Table 1 contains a sample of collected cases of unrequired actions in such situations.

Why do we not use the usual term, 'error of commission'? Firstly, it is too general ('incorrect performance of a task' [1]). Therefore, it does not have much signification from a psychological perspective. Secondly, it does not match PSA structure. When an action is required, there will be three possible branches in an event tree:

— correct action ('yes')
— no action ('no': omission or delayed action)
— unrequired action.

When no action is required, there are two possibilities: no action; unrequired action. Only unrequired actions will be modeled. A 'commission error' may be modeled either by a 'no action' branch (too early, too late) or by both a 'no action' branch and an 'unrequired action' branch (starting pump A instead of pump B: no action on pump B, unrequired action on pump A). The term 'unrequired action' better matches the PSA structure.

In our investigations, we concentrate on DUA. Decision-based means that the action is intended by the operator. Involuntary actions (like inadvertently touching a control, e.g. case 1 in Table 1) will not be addressed. Sometimes a deep analysis of the incident is necessary to determine whether an action was intended or not, e.g. cases #6 and #8 in Table 1. If there is any doubt due to sparse information, we recommend classifying the action as *intended*. The problem of such classifications (intended or not; mistake or slip) is also reflected by incident analyses of other authors.

> For example, in 1986, Reason classified the case #5 action (TMI, disconnection of high pressure injection) unambiguously as a skill-based slip ([11], p. 296). Four years later, he assesses that it involves both elements of a slip (strong-but-wrong interpretation) and a mistake (improper appraisal of system state; [12], p. 55).

Nevertheless, their significant safety impact confirms our restriction on those unrequired actions that are decision-based (i.e. intended). Given such an action, recovery factors are less effective. In most of the cases, external intervention is needed to recover the underlying error of intention [11,12].

Our work concerning the definition of the subject (DUA) has shown that the taxonomies of Swain and Guttmann [1], Reason [12] and IAEA [13] are useful for initial understanding of human actions concerning risk relation and error causation. However, without reference to real performance situations, their value is diminished. Therefore, it is strongly recommended that such taxonomies be used together with specific cases from operating or simulator experience.

Table 1. Cases of unrequired actions from nuclear operating experience. Other studies (e.g.NRC [2]) confirm that such cases are not of an exceptional nature

Action	Unrequired because...	Consequence
Case #1. PWR, Obrigheim, 1972, while performing scheduled purging of pressurizer relief tank: *control of drain valve inadvertently touched* [3,4]	...initial situation was safe, manipulation of drain valve is no component of scheduled purging	drain valve opened after touching of control, loss of coolant accident (LOCA)
Case #2. PWR, Obrigheim, 1972, after loss of coolant through open drain valve: *bridging the torque limit switch* of the valve [3,4]	...automatic safety injection would control the loss of coolant ([5])	drain valve could be closed, loss of coolant stopped
Case #3. BWR, Browns Ferry, 1975: *working with burning candle* for closeness check of a cable shaft [6]	...initial situation was safe, working with candle violates safety rules	cable shaft ignited, cable fire accident
Case #4. BWR, Brunsbüttel, 1978, after mainsteam leakage in turbine hall: *inhibiting automatic scram actuation* as part of the plan for the *location of the leakage* by inspecting the turbine hall [6]	...the loss-of-steam-related system functions worked properly, scram inhibition violates safety rules	leakage not located, significant safety function partially unavailable
Case #5. PWR, TMI-2, 1979, after loss of coolant through open pressurizer relief valve: *manual disconnection of the high pressure injection (HPI) pumps* [7]	...automatic HPI would have controlled the loss of coolant	loss of coolant until core damage
Case #6. BWR, Oyster Creek 1, 1979, while attempting to assure adequate natural circulation after trip of all recirculation pumps: *closing of two more discharge valves* (B and C) than required [8]	...natural circulation requires the closure of exactly two discharge valves (A and E)	failure of natural circulation, decreasing of core water level
Case #7. PWR, Davis Besse, 1985, after failure of the main feedwater pumps: *manual start of auxiliary feedwater pumps* [9]	...the emergency feedwater pumps would start automatically later on	starting failed, steam generators (SG) isolated, failure of both auxiliary feedwater pumps
Case #8. PWR, Philippsburg-2, 1987, while performing scheduled tests of the reactor protection system (RPS) during shutdown state: *disconnection of all emergency diesel generators* (EDG) from the actuation via RPS [10]	...initial situation was safe, disconnection of *all* EDGs (at the same time) is no component of scheduled RPS tests	significant safety functions partially unavailable
Case #9. PWR, Biblis-A, 1987, during required but unscheduled performance of plant shutdown: *attempting to close stuck open primary isolation valve* (PIV) via reflux by *opening a test pipe* between first (stuck open) PIV and second PIV [10]	...initial situation was safe, second PIV was closed, first stuck open PIV could be closed without problem under low pressure when shutdown is terminated	first PIV did not close via reflux after opening of test pipe, LOCA (via test pipe) outside the containment for short duration

2.2 Current practice in analyzing decision-based unrequired actions

To what extent do established methods cover the analysis of DUA? Established methods are those which are currently used world-wide in studies on PSA. The most well-known of these are, in alphabetical order: **ASEP** [14]; **HCR** [15]; **HEART** [16]; **SLIM** [17]; **THERP** [1].

If we refer to the written contents of the publications listed above, we would conclude that each of the methods is able to quantify the probabilities of decision-based unrequired actions. For the essential phase of such quantification, namely the identification of decision errors and of the essential performance shaping factors (PSF), the authors of the methods listed above recommend performing a detailed task analysis or applying other approaches such as confusion matrix [18]. However, only THERP presents guidelines on how to perform a task analysis in the context of HRA.

But THERP's guidelines do not adequately cover the identification of DUA—which are a subset of what THERP calls 'extraneous acts'. Firstly, the identification of extraneous acts is stated as a problem of pre-selection of the PSA-relevant ones:

> "Obviously, a person in a system performs many extraneous acts, e.g., smoking a cigarette, scratching his nose, and the like. In a system context, these behaviors are not considered errors unless they have potential for degrading the system in some manner" ([1], pp. 2–16).

In general, THERP admits that 'no hard and fast rules' can be given for error identification. Concerning extraneous actions, it is stated that their identification is extremely difficult and that the degree of completeness greatly depends on the analyst's expertise:

> "No one can predict unlikely *extraneous acts* by plant personnel, such as the use of a candle to check leaks in the negative pressure containment building (the Brown's Ferry Incident). Still, given sufficient time, a skilled analyst can identify most of the important tasks to be performed in a system and *most* of the ways in which errors are likely to be committed" ([1], pp. 4–9).

As a basic support for the identification of such errors and error-prone situations, THERP ([1], Fig. 4-2) presents a number of factors under the following five headings: (1) external inputs to human; (2) discrimination and perceiving; (3) cognitive activities and processes; (4) responses; (5) external results. The listed factors—which mainly concern psychological and ergonomic findings in human performance—are explained in more detail in several chapters of Swain and Guttmann's *Handbook* [1], especially in Chapter 3 ('Some Performance Shaping Factors Affecting Human Reliability'). They appear as a basic guide for identifying problems that concern man–machine interfaces (e.g. 'misleading feedback') or elements of cognition (e.g. 'conflicting goals'). However, explicit guidelines on how to identify and quantify elements of cognition in a PSA, especially those leading to extraneous actions, are lacking. This gap between basic explanations about PSF and guidelines for their incorporation in HRA is also reflected by the examples presented in [1], e.g. case study No. 2 in Chapter 21 of the *Handbook*:

> The analysis addresses the failure to switchover from injection mode to recirculation mode within two minutes as soon as an alarm warns (30 minutes after large LOCA) of an excessively low water level in the refuelling water storage tank. However, it does not consider the questions as follows: what happens if the switchover action would be implemented too early (i.e., before 30 minutes)? In which variants of an accident such switchover action may be unrequired or unwarranted? Which elements of cognition could lead to confusions concerning action timing or accident variant?

So, unrequired actions that aggravate apparently safe situations are seldomly addressed explicitly. However, Table 1 demonstrates that such actions do happen and contribute to risk.

2.3 Why do current human reliability analysis methods fail in decision-based unrequired actions prediction?

Given the little help that established methods present for the analysis of decision-based unrequired actions, it is not surprising that these actions are inadequately incorporated into current studies on PSA. This is no reproach of established methods. We know that we have to deal with a basic difficulty in HRA.

It seems that most HRA methods make too simplistic a use of the stimulus–organism–response (SOR) paradigm. To 'predict' the 'R', they focus on the 'S', and, more precisely, on those stimuli closely related to the prescribed response: *the prescribed task* (theoretical PSA event and external PSF). The operator is modeled as a relatively passive information processor. He is seen as a 'reactor', rather than an 'actor'. Thus, this HRA practice should perhaps be named *task* reliability analysis instead of *human* reliability analysis.

Such a use of the SOR paradigm is unsufficient for 'predicting' DUA. Much attention should be paid to the 'O'. According to "activity-oriented ergonomics", the operator is *actively* operating, i.e. modifying the work *situations* through the *signification* he ascribes to them [19,20]. This could result in a response which is not closely related to a stimulus considered as relevant for the prescribed task. Usually, the operator's activity is unequal to the prescribed task. This conforms with the authors' previous experience in HRA practice, for example:

> "The operator does not apply the procedure mechanically.... Every time an operator reads a procedure he *necessarily* interprets or 're-thinks' it" ([21], pp. 631).
>
> "... PSA for research reactor FRJ-2. Firstly, we (the PSA team) assumed that after LOCA plant personnel would give priority to preparing light water injection for the (anticipated) case that automatic heavy water injection would fail. However, a talk-through [with the operators in the 'field'] showed that priorities would be as follows: switching out the hooting accident alarm, and rescuing of workers from the [LOCA-affected] reactor hall" (translated from [22], p. 186).

Besides, even under well-defined laboratory conditions, the signification of the situation for the operator may lead to unexpected stimulus–response correlations. For instance, expectancy (predisposition to interpret information in a certain way [1]) often appears to be at least as important as the stimulus itself. This underlines the key role of *human characteristics*.

To some extent, existing taxonomies and models attempt to improve the current practice of SOR representation in HRA. Sabri *et al.*'s [23] retrospective analysis of incidents uses a taxonomy that includes a behavioral error category defined as human-initiated and which may result from an activity on the part of the human that *does not require an external stimulus*. Swain and Guttmann's ([1], Fig. 4-2) simplified man–machine model includes a *human–internal feedback* loop which may result from cognition-related factors such as *attitudes*, motivation, emotions, and the like. However, the sparse explanations of these factors confirm that they are not well understood in a system context, or that their inclusion is understressed. Thus, they cannot be easily implemented into predictive analyses of complex systems.

Against this background, the state of art of promising new HRA methods will be briefly evaluated in the next section.

2.4 Promising new methods and approaches

Several methods concerning improvements of established methods like THERP have been published. Many of them are summarized and evaluated in Swain [24], for example. Some even more recent methods—not presented in Swain [24]—partially concern our subject of research (DUA), namely in alphabetic order: **CES** [25,26]; **EDF**'s 'EPS 1300' HRA methodology [27,28]; **HCR/ORE** [29]; **INTENT** [30]. Evaluations of these relatively new methods can be found, for example, in Gertman and Blackman [31] or Reer *et al.* [32]. In addition to the methods listed above, several initial approaches or recently published procedures and methods are presented in Barriere *et al.* [33],Cooper *et al.* [34], Julius *et al.* [35], Hollnagel [36] and Reer [22,37].

CES and EDF 'EPS 1300' methodology include advanced concepts concerning the incorporation of *insights from operating and simulator experience*. CES derived factors about human intention formation from such experience, e.g. cases #6 and #7 (Table 1) are referred to in Woods *et al.* ([25], p. 180). EDF identified two cases of DUA (unwarranted shutdown of safety injection after a LOCA; unwarranted isolation of steam dump to the atmosphere after a steam generator tube rupture) from simulator experience, and took them into account in the 'EPS 1300' PSA [38]. EDF also stresses that information about the actual NPP context is of the utmost importance for HRA; especially information about the 'most human characteristics': *operator habits, attitudes, informal organization and practices* [28]. Recently published frameworks or methods for the analysis of errors of commission [33,34] use insights from detailed report-based events from operating experience, too.

HCR/ORE and INTENT use an advanced concept by *classifying errors according to their underlying mechanisms* and not so much according to their external accompanying circumstances. However, there is need for clarification of the employed definitions. Especially in INTENT, the theoretical basis of many relations between error type and PSF is not clear, and the PSF weighting procedure is not justified. HCR/ORE's methodological description only concerns failures of required actions.

There are promising works investigating the links between safety-related events and human characteristics. In a procedure for the analysis of errors of commission published in Julius *et al.* [35], three powerful operator-related performance influencing factors (e.g. expectation) are included. However, only three such factors are considered. And the related contextual factors should be presented more systematically. On this issue, the ATHEANA project [34] promises progress. ATHEANA's research on 'error forcing context' (EFC) appears to be an important attempt to renew the concept of 'error-likely situation' presented in Swain and Guttmann [1]. We appreciate the case studies on error mechanisms ([34], Chapter 5). However, at this stage of the project (1996), the active role of the operator still seems to be unsufficiently modeled. It is not clear how such phenomena as expectancy can match the underlying framework 'detection–situation assessment–response planning–response implementation'.

Jülich Research Center work [22,37] resulted in initial guidelines (illustrated by both hypothetical accident scenarios and real cases from operating experience) for the identification and quantification of decision-based errors. The underlying concept is based on the distinction between *s*ystem *f*ailure of *a*nalyst's *i*nterest (SFAI) and *s*ystem *f*ailure of *o*perator's *i*nterest (SFOI). Case studies demonstrate that a SFOI-vs-SFAI-related approach helps for both retrospective explanation of extraneous decisions—e.g. case #5 in Table 1, loss of core coolant level (SFAI—what happened) vs pressurizer overfill (SFOI—what the operator wished to avoid)—and their predictive identification in HRA. However, the guidelines need to be refined, on the basis of extended HRA applications and extended inputs from operating experience.

Furthermore, promising works of EARTH's members are in preparation. In Sträter [39] a data bank (based on German NPP operating experience) is created which allows for the assignment of a certain error type to a set of PSF constellations. A collection of systematic deviations from normative rational decision-making reference criteria is presented in Gerdes [40]. Ullwer [41] identified types of error-causing conditions by means of interviews with trainers about their supervisions of various NPP accident simulations. Preliminary results of these works are published in Gerdes[42,43], Sträter [44,45] and Mehl *et al.* [46].

The activities quoted above confirm that DUA are of major interest in current HRA research.

2.5 Conclusions from literature review

Cases from operating experience illustrate convincingly that DUA concern all categories of risk-related actions in NPP. Current HRA practice tends to neglect them because established methods do not contain adequate guidelines for their inclusion. Therefore, it is not surprising that a major field of current research attempts to fill this gap. Unfortunately, so far there is no practical HRA method that addresses DUA adequately.

Nevertheless, promising trends exist, namely:

- HRA should make more extensive use of insights from operating experience and simulator tests.

- Such information collection and interpretation, as well as modelling, should be based on an improved SOR representation, which emphasizes operator's characteristics and active involvement in the situation (while current representations mainly highlight the characteristics of the prescribed task).

This is why we found it necessary to discuss *event analysis methods* (Section 3) and to test the concept of *cognitive tendencies* for HRA purposes (Section 4).

3 EVENT ANALYSIS METHODS

3.1 Why is retrospective analysis necessary?

As we pointed out, operators are always actively involved in their work situations. To understand what is determining this active involvement, a systematic analysis of plant and simulator experience is necessary.

To summarize the state of current methods briefly, Section 3.2 gives a short overview of selected methods for event analysis. Afterwards, the main features of methods that have been developed by the authors are presented. Concluding remarks derived from our debates on retrospective analysis methods are presented in Section 3.3.

3.2 How should retrospective analysis be carried out?

3.2.1 Current practice
Looking at different methods for event analysis, the following principal approaches may be distinguished: classification systems and analysis methods.

3.2.1.1 Classification systems. Classification systems use a limited or open set of a task-, error- or PSF-related taxonomy to describe an event in a systematic manner. An overview of different classification systems is given in Wilpert *et al.* [47]. A well-known method in this field is ASSET (assessment of safety significant event team). After splitting an event into different occurrences, ASSET performs a root cause analysis for each occurrence of the event (see IAEA [48] and Okrent and Xiong [49], for example). For summarizing overviews see also IAEA [50] or SVA [51]. ASSET gives priority to the retrospective identification of causes of incidents, but it focuses on the analysis of organizational and management factors. However, events result from a complex interrelation of organizational factors as well as ergonomic and personal factors.

3.2.1.2 Analysis methods. Analysis methods go one step further by analyzing the error mechanism and interrelations between tasks, errors and PSF of organizational, ergonomic and personal nature. For instance, a typical interrelation between two PSFs is 'bad ergonomic design' that is compensated by the 'knowledge of the operator'. The above-mentioned classification systems may describe such an interrelation only by using two separate descriptors, design and knowledge: the causal link cannot be described with these methods (e.g. both descriptors may be used for two independent failures within one event). Analysis methods are rare but have the advantage of depicting the complexity of possible events by going beyond simple description and classification of causes. One example is the human system (HSYS) method [52]. However, this method is still not empirically validated nor does it emphasize coherencies between context effects and decision-based unrequired errors.

Discussing both methodological approaches, one has to be aware that these methods mainly focus on causes and not on the errors that occurred. Usually, errors and causes are treated by one descriptor and, because of this, the deeper understanding about the situation gets lost, as the following example shows: if a method uses an abstract descriptor (e.g. 'procedure') to describe what happened in an event, this does not distinguish whether an error (e.g. 'Procedure not followed') or a PSF (e.g. 'Bad design of Procedure') is meant. Also, positive effects of PSF are not considered.

Another problem is the representation of event dynamics: a previous management error (e.g. decision not to buy a new tool) may become a PSF for the operator who performs a physical action in the plant later on. The same holds for a maintenance error that has lead to a latent failure. For the operator those previously made errors become PSF in his working situation (e.g. insufficient tools or latency of possible side effects). Such *combinations* of errors and causes in the *dynamics* of the event are not clearly represented in these methods (cf. Sträter [39]). Concluding, complete analysis should concern:

- Possible errors (omission, commissions)
- Possible causes (PSF)
- Possible error situations or error-dynamics (interrelations of PSF, implications of previous errors, dependences)

The methods outlined above do not adequately address typically decision-making factors, and especially those factors to be considered if the operator is not seen as a 'stimulus responder' within the SOR model. Due to this, it may be concluded that approaches of current practice contain little information about relevant aspects that are especially of importance for analysis and assessment of DUA.

3.2.2 Introduction of methods including partial improvements
At GRS, based on the criticism of current approaches for event analysis, a situational analysis approach was developed by Sträter [39]. The method consists of a systematic structure for event analysis in which an open list of taxonomies may be used (task taxonomy, error taxonomy and PSF taxonomy). It was implemented as a database named CAHR (connectionism assessment of human reliability; see Sträter [45]). Fig. 1 gives an overview of the procedure. The method first performs an event decomposition, and secondly

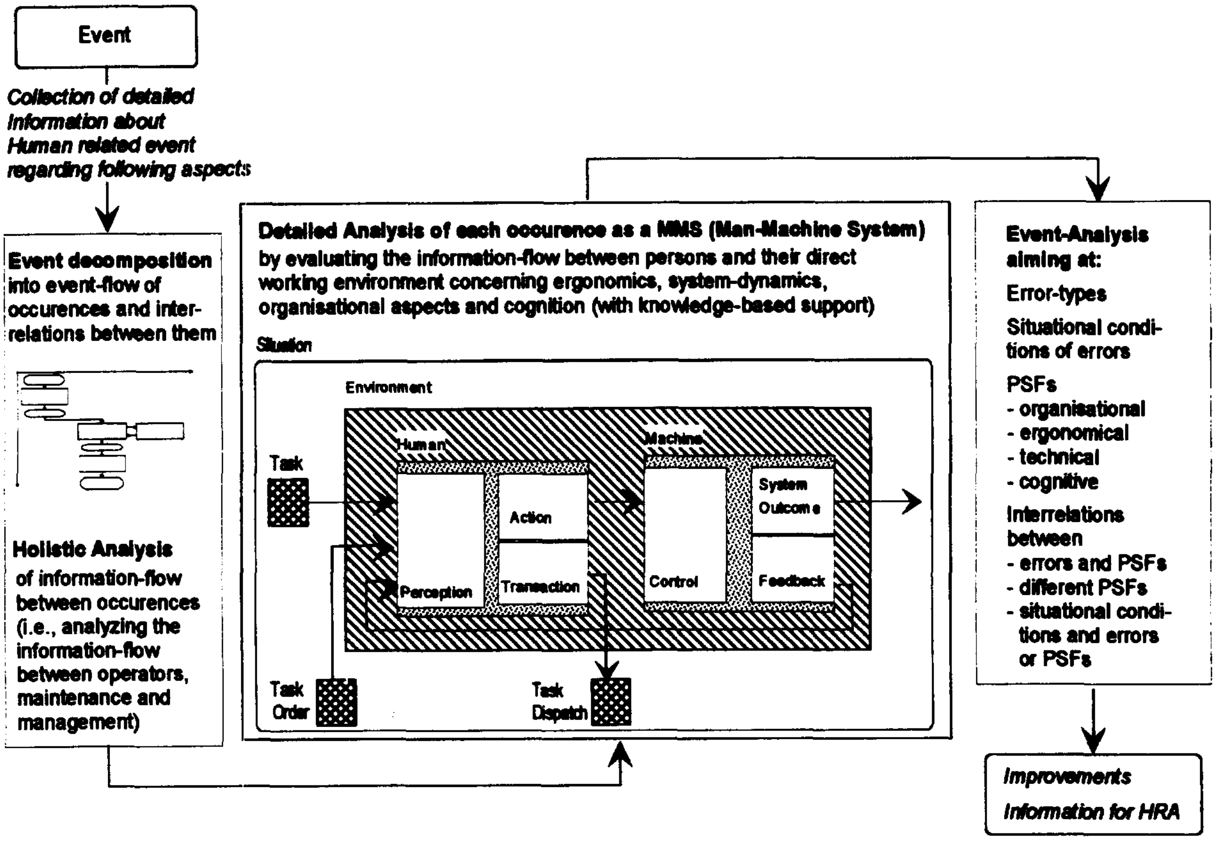


Fig. 1. Overview of the CAHR procedure for a situation-related evaluation of plant experience.

a detailed analysis of the identified erroneous actions. For this purpose, the affected system components, the errors that have been observed within the working system and the accompanied PSF are analyzed. The framework includes ergonomic, cognitive, organizational and system-related aspects of human reliability in the framework of a man–machine system (MMS).

An important aspect is the distinction of the 'task' and the 'task order'. The task is what the operator has to do (as defined for instance by a hierarchical description). The 'task order' is the way the task is introduced to the operator (e.g. by administrative order, by oral instruction). This term enables an important aspect of communication within working systems to be addressed.

An advanced knowledge-based system provides the analysts with most probable PSF or errors that were observed in comparable events or mentioned in literature. Because sufficient information may not be collected in every case with the first event-report, this feature enables handling of incomplete event information and use of historical information to support and minimize the efforts in analysis and classification of a new event. The algorithm of the knowledge-based system also enables a qualitative and quantitative prediction of human reliability on the basis of collected events [53,54]. For this purpose, it uses a compatible scheme and procedure for event description/acquisition as well as for the assessment.

Since the approach is flexible ('open'), the predictive power may be improved by further collection of events. Major features are: (1) it allows a compromise between free text analysis (open analysis form) and fixed descriptors (closed analysis form); (2) the richness of the situation (i.e. the error dynamics and context) may be described; (3) it is able to find similarities between different events or to subsume different events regarding an actual question, which is important for generating statistical data from the detailed information; (4) interrelations of PSF and errors can be analyzed (e.g. PSF influencing cognitive behavior); (5) probable errors or PSF for a given situation can be predicted.

Though the first results are promising, future validation studies will have to confirm the predictive power. Also the applicability of the tool has to be improved to assure a completion and extension of the data-base.

At KEMA, a method to identify and analyze cognitive errors (MICE) was developed [40]. MICE is a computer-aided standardized method for event analysis. The method can be used for detailed analysis, forcing the analyst to think about how the operator had to solve the problem (operator point of view, not designer oriented). A structured cognitive error classification that underlies the method comprises 55 errors that were built from 13 basic error types. Furthermore, it provides a detailed classification of PSF that were derived from a literature review of 32 sources. A mapping of errors to PSF is employed to attribute context to the errors. The method provides detailed information about cognitive errors and their context. Its application may lead to questions about operator's beliefs and attitudes. A limitation of the method is that through a decomposition of the event into occurrences, the interaction and dynamics of the occurrences may be lost.

EDF developed an approach for detailed event analysis [55]. It is made up of five steps:

1. *Information collection*: parameter-records, shift book, technical analyses, and—very important—interviews with the operators. The goal of this step is to know (as much as possible) what actually happened.
2. Description of the *temporal and logic chain of facts*, considering the man–machine system as a whole. At this step, the real and potential consequences of the event are also examined.
3. In-depth analysis of the *deviations from prescriptions* (which deviation, which causes?).
4. Analysis of the *factors involved in the decision-making process*, from the operators' point of view. These factors are related to the situation (prescribed task, formal and informal organization, man–machine interface, etc.) and to its signification for the operators (based on their experience, attitudes, goals, etc.). Operators' decision-making for each main action can thus be described by a balance of a number of elements of arbitration. This is a way to illustrate the trade-offs which lead to the decisions.
5. Definition of corrective actions.

The method is useful for in-depth analysis. It is open and therefore can be applied to various cases and does not constrain interpretation too much. However, more developments are needed concerning the human factors aspect of the analysis (especially for steps 3 and 4). Analysts should be provided with more guidance for richer interpretations of the causes. Otherwise, the corrective actions proposed will too often be 'improve the procedure' and 'tell the operators not to do so'!

At the Jülich Research Center, Reer [56] developed a method that contains an open list of guidelines based on insights from previous retrospective analyses (e.g.[57–59]). As a scope-setting principle, it is recommended in this method to compile a very 'short story' that includes *all* unusual occurrences and their *essential context* without excessive technical details. Then the analysis should envisage major PSA-related occurrences first. For their description, the method presents a list of criteria (i.e. items for data acquisition) which are easy (i.e. objectively, as free from judgement as possible) to obtain on the one hand and which have been proved to be useful for causal analysis on the other hand. For instance, for each incorrect human response occurred, the analyst will look for: the underlying goal or plan if it is self-evident (e.g. the plan to close a stuck-open valve, see Table 1, case #9); the anticipated correct response and its consequence; the underlying task and sub-task; the underlying sequence of events. Guidelines that are mainly of holistic, comparative and generalizing nature are provided (see Table 2 as a simplified illustration). For instance, it is recommended to consider:

- an occurrence not separately, but within the context of a 'wide-enough defined' sequence of events (e.g. in Table 2: not only the second check is considered, but also the first check, although it was successful);
- similar situational patterns from other incidents (e.g. by Wustmann [60]: an error that occurred at the end of procedure when the problem was *almost* solved);
- the common presence of several items.

3.3 Conclusions from the discussion of event analysis methods

By applying the methods discussed to cases and by discussing the analyses within the group, conclusions were drawn concerning several important issues.

Table 2. Simplified illustration of a causal analysis by using guiding principles of holistic, comparative and generalizing nature

Guiding principles	Obtained results
Holistic view of the occurrence-underlying sequence of events	Simplified sequence from the Browns Ferry incident (Table 1, case #3): First check with candle → leakage detected and sealed → second check with candle → *cable shaft ignited* in presence of a sucking air stream due to remaining leakage.
Comparative view of the sequence-underlying events	*Question to be raised*: Both checks were performed in the presence of a leakage. Why did the first check succeed, and why did the second one fail?*Plausible answer*: The first check resulted in sealing of a leakage (success). Thus, during the second check the operator did not expect a leakage anymore.
Generalization of system-specific findings	*Causal factor*: Reduced vigilance after perceiving essential success.
Comparative view of similar retrospective findings	*Confirmation of the causal factor*: Other occurrences from operating (e.g. Wustmann [60]) and simulator (e.g. Mehl *et al.* [46], Ullwer [41]) experience.
Generalization of system-specific findings again	*Recommendation for improvement*: Incorporation of special alerting factors in those critical procedure steps subsequent to a step that is likely to be perceived as an essential success.

3.3.1 Combining open and closed methods

Event analysis within an 'open' classification (i.e. flexible taxonomy and structure of errors and PSF) may lead to a high variability in analyses. Another common disadvantage of such a procedure is the high dependence on the analyst's expertise. Only well-trained human-factor specialists will be able to choose and identify causal factors. However, such methods are well adapted for in-depth detailed event analysis.

Event analysis within a 'closed' classification (i.e. fixed taxonomy and structure of errors and PSF) may lead to analysis deterioration, since the information is acquired according to the analysis-scheme rather than to the specific aspects of the event. Concerning possible PSF, 'closed' classifications are normally incomplete. However, such methods are needed for analyzing many cases in a standardized way for statistical treatment.

To assure both advantages, a good methodology should combine open and closed features (cf. Sträter [39]). It should also support the analysts by (1) collecting information about the context of an event and its relationships to cognition systematically, (2) finding error-prone situations or error opportunities and PSF (this includes using an open object-, task-, error- and PSF-taxonomy), (3) finding similarities between events regarding qualitative and quantitative data about man–machine interface, organization and operators.

3.3.2 Making clear distinction between facts and assumptions

As the information about events is sometimes rather scarce and difficult to collect in the necessary detail, analysts have to make many assumptions and interpretations. However, very often no clear distinction is made between well-established facts and assumptions. In this case, proposals to improve the man–machine system or administrative procedures will be made on a weak or even unknown basis. There is a high risk of spending money and effort for changes that actually are 'justified' only by an insufficient or wrong assumption. Therefore, event analysis should explicitly discern the known, observed, explained facts and the assumptions and interpretations. This includes being able to describe different paths of explanations for one event.

Such a practice would also show how well-established information is often lacking. It would induce analysts to improve their information-collection methods (in particular, interviews with operators). Finally, we suggest that event analysts should consider methods for selecting information sources and for interpreting information that were identified as being of high value in history or hermeneutics.

3.3.3 Combining designer-centered analysis and operator-centered analysis

Event analysis usually stresses information about 'external PSF' and what the operators should have done (designer centered analysis). In order to get insights into 'internal PSF' (operators' feelings, attitudes, why they acted, which compromises they made, what was the signification of the event for them, etc.), the analysis should also be performed 'from the operators' point of view' (operator-centered analysis). Of course, this kind of analysis is difficult and implies getting good information and making a rigorous distinction between facts and assumptions.

3.3.4 Giving narrative descriptions of events

Event descriptions are very often static, though operators experience events as highly dynamic and complex situations (see for instance Frederick's statement about the TMI incident [61]). The operators have to find a compromise between various constraints and goals. Their actions are results of trade-offs. Moreover, this may be accompanied by time pressure. Narrative story-like descriptions of events will help to explain such dynamics and will therefore be useful for operator-centered analysis. To get a better view of the context of the unsafe action, naturalistic inquiries may be applied [62].

3.3.5 Describing the context of unsafe actions

An important aspect for the analysis of DUA in their specific context is a systematic consideration of the interrelations between the different aspects of the situation. For this purpose, the context has to be defined. It consists at least of the prescribed task, the information from the system, and the characteristics of the situation (e.g. time constraints) or of the technical system (e.g. dynamics) as well as the relationship of the operators with their management and organization. All these aspects together build the error situation or error context. Trying to identify some characteristics of the situation not present under more typical or nominal conditions ('aleatory aspects' as they are called in Section 4.2.1) is particularly useful.

3.3.6 Ensuring confidence and confidentiality

Decision-based unrequired actions result from complex interrelations between situational constraints and cognitive mechanisms. Hence, the term DUA is not associated with any type of guilt. The analysis of plant experience must neither blame nor burden the operator. Besides, confidence and confidentiality are necessary for good information collection.

3.3.7 Stressing positive aspects of operators' activity

As event analysis usually aims at tracking defects, it focuses on operators' errors. It should not be forgotten that most of the time operators succeed and have a crucial role in optimizing operation and recovering troubles or failures. Knowing how operators recovered an event, why it did not propagate, is as important as explaining failures and errors. Moreover, pointing out positive aspects of operators' activity is important for establishing a good and confident climate on a plant and between operators and HRA analysts.

Applying these proposals implies that a multidisciplinary approach and analysis team are used. It should also be pointed out that the source of information about an event, and the information collection method, are at least as important as the analysis method itself.

Regarding the understanding of DUA, we also concluded that:

- The context of the DUA may be considered as a complex physical, psychological, organizational and social environment of the operator that may be described as an extended man–machine system.
- The context may lead to several tasks that the operator sees to be important in a given situation. These tasks result in real or perceived constraints for the operator. He has to cope with the perceived constraints of the context and has to find a compromise between them. The operator's final action is a result of solving the trade-off between the situational constraints and the aims he built. The cognitive dissonance theory may be useful to explain such behavior of the operator (cf. Reer and Sträter [63]).

4 COGNITIVE TENDENCIES

4.1 From operators' current practices to cognitive tendencies

The study of operators' behavior, in particular during simulated accidents, shows that their *current practices*[1] *(or habits) under normal operating conditions continue to affect their actions in troubled conditions* to a large extent. This may be a cause of errors, and in particular of DUA, since these practices are sometimes inappropriate to the troubled conditions. Thus, operators will use a temperature gradient indicator which is not valid in thermosiphon conditions, or use systems such as pressurizer spray inappropriately. Operators' decisions are also affected by their values[2] and, more generally, their attitudes.[3] We can thus associate operators' reluctance regarding actions that have a negative impact on production or equipment with these notions.

Moreover, the emphasis put on these notions for HRA [28], on the basis of empirical observations, is consistent with what we said in Section 2.3 about the limitations of the current SOR representation in HRA. The notions of attitude and value clearly go beyond the paradigm of the 'information-processing operator'. They introduce *subjective aspects*. As soon as we speak of the attitudes and values of the operators of a plant or of a company, we also introduce *collective aspects* (see the definition of 'values' in footnote).

These ideas can be re-assigned in the framework of the evolution that has led the nuclear industry to dwell on the significance of 'safety culture'[4] ([64,65]). In addition to knowledge, this notion highlights subjective aspects—commitment, motivation—as well as collective and organizational aspects—supervision, responsibility—(the terms between dashes are proposed by the INSAG 4 group). The INSAG 4 group writes about the definition they give for safety culture (see footnote): 'This statement was carefully composed to emphasize that safety culture is an *attitudinal* problem as well as structural, that it relates both to organizations and individuals.... The definition relates safety culture to personal attitudes and *habits of thought* and to the *style of organizations*' (our underlining).

Although they may be too vague, the notions of practice, value and attitude thus seem to be of interest for investigation with respect to HRA generally speaking, and DUA in particular. In order to simplify matters, in a first phase, the EARTH group has adopted the generic term of 'cognitive tendencies'. This is a composite notion that can at present be defined as follows: 'typical habits or attitudes of humans in decision-making'. In order to define this notion, and better to appreciate its interest for HRA, the group has adopted two complementary approaches that are presented in Section 4.2 and Section 4.3.

4.2 Cognitive tendencies in the nuclear context, illustrated by case studies

Our first approach was to look for examples of NPP operators' 'cognitive tendencies' in our experience and from a common analysis of some incident cases. To describe our examples, we found it necessary to use an improved representation of the SOR paradigm. We shall first present this model. Then, we shall explain our examples of 'cognitive tendencies'. Finally, we shall illustrate them with the incident cases analyzed by the EARTH group.

4.2.1 A human-centered model

In Section 2.3, we pointed out that the current use of the SOR paradigm is inadequate for the prediction of DUA. From de Montmollin [20], we derive an improved representation, a *human-centered model*, as illustrated in Fig. 2.

With the word *'situation'* this model points out that real events are more complex than a mere combination of a signal with a set of PSF. In particular, the situation combines predefined aspects (prescribed task) with aleatory aspects.

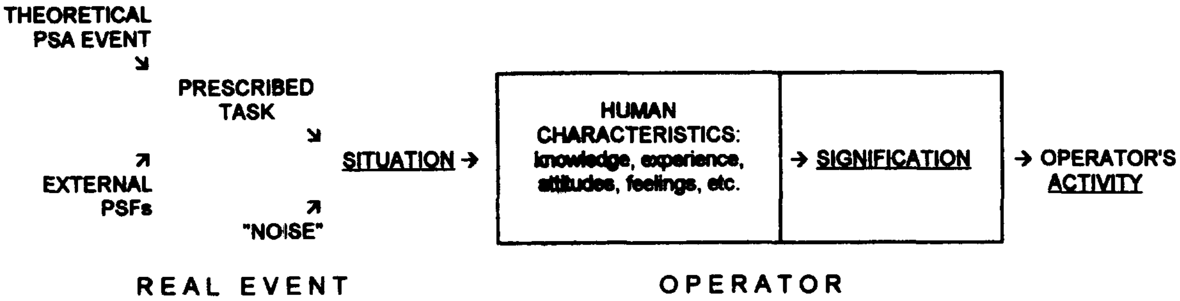
---

[1] Practice: 'A habit, custom; (with plural) a habitual action' (*The Shorter Oxford English Dictionary*, 3rd edn.)

[2] Values: 'The social principles, goals, or standards held or accepted by an individual, class, society, etc.' (*Webster's New World College Dictionary*, 3rd edn).

[3] Attitude: 'Settled behavior or manner of acting, as representative of feeling or opinion' (*The Shorter Oxford English Dictionary*, 3rd edn).

[4] According to the INSAG 4 report (IAEA [64]): 'Safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance'.



- REAL EVENTS ARE COMPLEXIFIED BY "NOISE"
- THE OPERATORS ARE ACTIVELY OPERATING, I.E. MODIFYING THE WORK SITUATIONS THROUGH THE SIGNIFICATION THEY ASCRIBE TO THEM
- OPERATOR'S ACTIVITY ≠ PRESCRIBED TASK

Fig. 2. A human-centered model.

There are always several slight misadjustments on a plant: delays, minor leaks, minor departures from nominal flows, position indicator or display failures, spurious alarms, etc. When they combine with more severe events, they make the situation more complex. These aleatory aspects can be called 'noise'. However, it should be stressed that, in our model, this 'noise' may not only alter the 'signal-to-noise-ratio' *quantitatively*, but even *qualitatively* change the stimulus for the operator. A non-nominal aspect which looks minor from outside may be very meaningful for the operator, due to his own experience. What really directs the operator's actions is the *signification* of the situation for him. Therefore, the important factors in a situation depend on the operator himself, and may change from one operator to another, or, at least from one population to another. The operator is not passive, not only reactive, but 'pro-active'. Due to the complexity of real situations and to the active role of the operator, operator's *activity* is not identical to the prescribed task. Operators make adjustments and *have* to do so, to cope with the complexity of real situations. As de Montmollin says, 'operators are actively operating, i.e. modifying the work situations through the signification they ascribe to them.... The play has not to be recited, it has to be interpreted, and sometimes improvised'. This model expands the role of the 'O' within SOR, to better take account of the 'immense richness of the "O"' [66].

4.2.2 *Examples of NPP operators' cognitive tendencies*

These examples are given in Table 3 and are commented on below.

It was difficult to find a trade-off between the requirements for simplification imposed by HRA and the need to resist oversimplification. Coming back to our proposed application of the SOR paradigm, Situation - Signification - Activity, we found that a tendency could be described in terms of these three 'dimensions'. The aspect of the tendency related to the *situation* is a set of 'situation factors'.

Another dimension of a tendency concerns the *signification* of the situation for the operators. These 'elements in operators' interpretation' are related to operators' knowledge, experience, and attitudes, and to general human characteristics. They could be considered to be some kind of 'interpretation rules'. Since they are not necessarily well structured, precise, systematic or compelling, we prefer using the words 'elements in operators' interpretation'. *The combination of 'situation factors' and 'elements in operators' interpretation' will increase the probability of occurrence of a given behavior.* This behavior relates to the third dimension of the tendency, i.e. *activity*. 'Situation factors,' 'elements in operators' interpretation', and 'behavior' are closely related and can hardly be considered independently from each other.

For each tendency, there can be various combinations of the 'factors' and 'elements' in the Table 3. Besides, there is no systematic correspondence between 'factors' and 'elements' on the same line in the table. A combination of at least one 'factor' and one 'element' is needed for the related tendency to be 'activated', i.e. for the probability of the related behavior to be increased. If there are more 'factors' and 'elements' in a case, the probability of the behavior may be even higher.

As will be developed below, tendencies can in fact result in extremely efficient actions or, on the contrary, errors, depending on circumstances. Given the subject of interest to us here (DUA), in Table 3 we consider only the negative manifestations of tendencies. In addition, we deal only with disturbed situations (incidents and accidents, or less severe disturbances, such as delay in time schedule, abnormal system state, unexpected event, etc.).

Each tendency is given a name for easy identification. Because of the composite nature of a tendency and the complexity of the notion, these names are obviously simplistic. In other words, saying that 'the operators of a NPP are eager to act' would be meaningless: on the contrary, under many circumstances they could in fact *delay* actions (this is indeed the case in the 'Reluctance' (CT2) tendency).

4.2.2.1 CT1, 'Eagerness to act'. During troubled conditions, operators are often inclined to perform actions

Table 3. Examples of nuclear power plant operators' cognitive tendencies related to DUA

CT 1—Eagerness to act

Situation Situation factors	*Signification* Elements in operators' interpretation	*Activity* Behavior
Disturbance and:		
—operators must wait and not act	—acting reduces the tension and stress associated with waiting	
—present or foreseeable time constraint	—acting makes it possible to create a margin, to reduce the time constraint, workload, and present or subsequent stress	anticipated action(carried out prematurely)
—events in progress have detrimental consequences on equipment, availability, or safety	—it is difficult to resist 'trying to do something' while events with serious consequences are occurring	

CT2—Reluctance to undertake unusual actions or actions with negative consequences

Situation Situation factors	*Signification* Elements in operators' interpretation	*Activity* Behavior
Disturbance and:		
—manual action to be carried out (or programmed automatic action) detrimental to equipment, production, or the reputation of the NPP	—operators hope that the situation is indeed the most probable one, i.e. the least serious (see CT 4); in that case, the action appears to be disproportionate to the problem to be overcome	—omission or delay in the performance of the manual action
—manual action to be carried out (or programmed automatic action) could jeopardize staff safety or plant safety	—even if the seriousness of the situation is properly appraised, the operators—used to overcoming multiple contingencies and very familiar with the equipment—hope to find solutions better suited to the situation encountered than the 'standard', 'envelope' solution in the procedures	—inhibition or interruption of the automatic action
—the automatic action in question is sometimes inadvertent	—operators do not properly understand the unaccustomed action or think that there is an error in the procedure	
—action to be carried out contrary to operators' 'normal operation' habits		

CT 3—Fixation

Situation Situation factors	*Signification* Elements in operators' interpretation	*Activity* Behavior
Disturbance and:		
—new information arises during the event, requiring evolution of the diagnosis, objectives, or strategies adopted	—operators are mobilized for the actions in progress	—failure to take account of new information
—actions different to those in progress have to be carried out	—stress reduces their field of perception and analytical potential	—unrequired actions performed due to failure to take account of new information
	—consideration of new or 'atypical' elements is perceived as disturbing because it would increase workload and stress	—omission of 'atypical' action (relative to the actions in progress)
	—'filtering' mechanisms are vital in order to 'keep concentrated' and successfully complete a task	

Table 3. (continued)

CT 4—Subjective probabilistic reasoning

Situation Situation factors	*Signification* Elements in operators' interpretation	*Activity* Behavior
Disturbance and: —rare event	—it is impossible to deal with all possible causes. Causes are therefore ranked with implicit probabilistic reasoning	—failure to diagnose or late diagnosis of the event
—event with detrimental consequences	—in real time this probabilistic reasoning cannot be pursued systematically and completely rationally (e.g. difficult to take account of probability and consequences at the same time)	—a more probable event is diagnosed instead (particularly spurious startup of the safety system concerned or instrument failure)
—event that cannot be definitely associated with the recent history of the plant	—the estimation of probabilities is affected by the operator's previous experience and his knowledge about the situation and his goals	
—certain manifestations of the event (startup of safety systems, alarms, values of parameters) can be attributed to more frequent causes (equipment failures, transients, etc.) or causes encountered recently	—unconsciously refusing to take account of severe consequences (psychic defence against fear)	
	—overweighting suitable (i.e. less disturbing) information	

sooner than required by the procedures (anticipating actions). The action can have a *direct* role in reducing stress and 'letting off' nervous tension. This can be the case in 'wait and see' situations in particular—waiting for a threshold to be attained or for an automatic action to take place—which appear to be quite stressful.

The action can also have an *indirect* role in the reduction of stress and, more generally, optimization and organization of the operators' working conditions: operators will try to *get margins* for working with lower stress and a lower work load (search for 'operating comfort'). For instance, they will anticipate actions (carry them out prematurely) to reduce subsequent time constraints (save time later). Lastly, operators can find it difficult to let certain events they consider to be detrimental take place. This is no longer a question of self-protection (from stress), or of protecting the work situation (search for 'operating comfort'), but of protecting equipment, availability, or safety (tendency CT2 is an 'inverse' manifestation of the latter point).

4.2.2.2 CT2, 'Reluctance to undertake unusual actions or actions with negative consequences'. Operators can be reluctant to undertake certain actions, especially:

- if the consequences of the actions appear to be disproportionate to their contribution;
- if the actions are contrary to the operators' control habits (and, of course, more generally, if the operators do not understand them properly).

In both cases, they can think that the procedure is not optimal for the real situation, or even that it is erroneous. This appreciation can also concern automatic actions. Operators assess the consequences of actions in accordance with parameters that may be different from those taken into account by the specialist who wrote the procedure or who designed the automatic safety system (because operators have to optimize in accordance with the multiple constraints of the real situation).

Nuclear power plants are looking to reduce excessive demands on equipment and production losses, which is normal. This leads to quantitative objectives (e.g. number of automatic reactor shutdowns per year) and sometimes to informal challenges between NPP. Operators also have experience with inadvertent start-up of safety systems. When a safety system starts-up, it is most likely that it is inadvertent. Moreover, since safety systems are set up with a good degree of conservatism, their solicitation may appear really disproportionate to the conditions. Any shortcomings or too much conservatism in the procedures can have the same impact. Moreover, the operators can have an almost emotional link with the equipment they operate, and therefore be reluctant to undertake detrimental actions on that equipment.

In this context, the actions most frequently given as likely to be subject to reluctance are automatic reactor shutdown, safety injection, containment spray and switching to a feed-and-bleed cooling mode.

4.2.2.3 CT3, 'Fixation'. This tendency is associated with certain aspects of the *dependence* phenomena which are so important in HRA. To use a popular expression, it can be said that operators are inclined to 'stay on the rails' they have switched on to at the beginning of an event or of a phase in that event. This tendency is exaggerated by stress and can be very strong under accident conditions. It can be characterized by:

- at the level of the search for information: information likely to invalidate the initial diagnosis or to require a modification of the objectives or of the adopted strategy will be taken into account less easily than that implying no modification.
- at the level of decision making or of the performance of the action itself: it will be harder to initiate operations of types different to the current ones (the factors of similitude between actions can be of various types).

4.2.2.4 CT4, 'Subjective probabilistic reasoning'. Implicit probabilistic reasoning is indispensable for ranking of events and for reasonably quick orientation among the multiplicity of possibilities. But this reasoning can be affected by the typical biases mentioned in the literature (see Section 4.3).

4.2.2.5 Beyond Table 3. Table 3 is in no way intended to be exhaustive. Other typical behaviors have been observed by members of the group, namely:

- root-cause orientation in corrective-action selection or continuation, or in system-state identification;
- overconfidence in the reliability of one's own performance (including both diagnosis and execution of actions);
- reduced vigilance when perceiving essential success;
- omitting to call for help when needed (to save face, prestige, pride, etc.).

Some details about these findings are presented in Appendix A. Complementary analyses would be necessary to confirm:

- whether they can be described in terms of the three dimensions (situation, signification, activity) proposed above;
- whether they can be associated with 'situation factors' that are characteristic of HRA sequences; and
- whether they can be considered to be 'cognitive tendencies' in the same way as those of Table 3 and be used in HRA.

Table 4. Summary of incidents analyzed in a feasibility study of cognitive tendencies. Human-related occurrences concerning the core of each incident are indicated with bold numbers. Obviously, there are more human-related occurrences, e.g. #1.1 or #2.1. However, we assessed them to be secondary, because they belong to 'other stories' which should be analyzed separately. Each critical action—be it an unnecessarily committed one or one that should have been committed—is underlined

	Occurrences and context
INCIDENT #1	After several delays (occurrence #1.1) due to 'slides' in scheduling, a test on the auxiliary feedwater system (AFWS) has to be carried out. The operator *performs the test at a power higher than required* (**#1.2**) (he does not appreciate the potential risk of such an error (overcooling)). After the test, a steam dump valve remains jammed half open due to mechanical failure (#1.3). The operators do not see the expected 'valve closed' indication on the mimic diagram, but suspect that the indication given is erroneous since limit-switch problems have already been reported. To confirm their diagnosis, they check that the closure order has indeed been sent to the valve. Therefore, they do not *isolate the leak* (**#1.4**) which is the cause of the cooling of the reactor, and attribute cooling entirely to the test that was not performed in nominal fashion. The crew believes it has the situation under control, and the operators *inhibit safety injection (SI) when the first criterion appears* (**#1.5**). Subsequently, the operators do not refer to an emergency procedure (although need for it is annunciated by an alarm); instead, they apply a normal-operation procedure (which would be correct for the absence of #1.3), and, according to this procedure, they *inhibit SI at its second actuation criterion* (**#1.6**). Later on, the shift supervisor detects the worsening of the situation, looks for the cause, detects the valve stuck open, and asks for the valve to be closed.
INCIDENT #2	Before initial startup, operators check the leaktightness of the reactor cooling system (RCS). They do this by setting a pressure of 112 bars for the RCS. However, in spite of this action, the pressure remains below 112 bars because of a spuriously open valve (occurrence #2.1). They *continue to increase the pressure* (**#2.2**), but the pressure still remains below 112 bars. Then they start to diagnose the unexpected low pressure. They detect the erroneously open valve and close it, but they omit to *reduce the pressure* (**#2.3**). Thus, serious RCS damage occurs due to overpressure.
INCIDENT #3	Loss of main feedwater (occurrence #3.1) during power operation. Operators decide to *actuate AFWS* manually (**#3.2**) before its programmed automatic actuation. While attempting this, an operator pushes the wrong pair of switches (**#3.3**), resulting in *isolation of both SG* and subsequently in an overspeed trip of both AFWS pump turbines. The shift starts to recover AFWS failure by sending operators to the failed equipment. About 7 min later, both SG are essentially dried out, and the procedure requires initiation of feed-and-bleed cooling (FBC). However, the shift supervisor decides not to *initiate FBC* (**#3.4**), but to continue recovery of AFWS failure. Three minutes later, the pilot-operated relief valve (PORV) opens for the third time and fails to close (#3.5). Perceiving the 'CLOSED' valve actuation signal, but failing to refer to the 'OPEN' valve position signal (although it is annunciated by an alarm), the operators fail to *detect the stuck-open valve* (**#3.6**). However, an operator *closes the PORV block valve* (**#3.7**) as a precautionary measure. Two minutes later, the operators succeed in recovering from AFWS failure.

4.2.3 Illustration of cognitive tendencies based on incident cases

The incidents used to illustrate our examples of cognitive tendencies are summed up in Table 4. The group has relied on more detailed descriptions (especially for cases 1 and 3). Some more elements concerning the analysis are documented in Appendix A.

The incidents involve 16 occurrences (in the sense of deviations from the reference), 11 of which are directly human-related and concern the core of the respective incident. Six of the human-related occurrences are committed actions which can be classified under the heading of DUA; namely: (#1.5) first inhibition of SI; (#1.6)second inhibition of SI; (#2.2) continuation of pressure increase; (#3.2) initiation of AFWS start, and, subsequently, (#3.3) isolation of SG; (#3.7) closure of PORV block valve. For two reasons we analyzed occurrences concerning omitted actions too: firstly, as shown in Table 4, they contribute to the context of DUA-related occurrences; secondly, we assume—and mainly have shown—that many omission-related 'cognitive tendencies' can be adapted for DUA.

Every decision is a trade-off between different factors and constraints. The following examples are taken from incidents #1 and #2 which are summarized in Table 4; they show the different factors (PSF) and cognitive tendencies that play a role in the decisions operators make. These examples illustrate Section 4.2.1. and complement Table 3 by showing the interconnections between the various factors involved and their relative importance.

4.2.3.1 Example 1: (Incident #1) Premature performance of the test, i.e. before the required initial conditions are reached (#1.2). Cognitive tendency activated: 'Eagerness to act'—CT1—of Table 3.

The operator is subject to a very strong time constraint—PSF1—(test delayed several times, cumulated delays and shift relief close); he carries out the test ahead of the due time in order to reduce time constraints, particularly because he incorrectly assesses the risk of this anticipation (novice operator—PSF2—) and since the level of compulsion of the instruction is low—PSF3—.

The contribution of CT1 is deemed to be preponderant in premature performance of the test.

4.2.3.2 Example 2: (Incident #1) The crew does not diagnose the secondary coolant break and erroneously attributes reactor cooling to the non-nominal test carried out previously (#**1.4**). Cognitive tendencies activated: 'fixation'—CT3—and 'subjective probabilistic reasoning'—CT4—of Table 3.

Having observed the non-nominal conditions under which the test of the auxiliary feedwater system was performed, the shift supervisor lowers the control rods: these actions (test and drop in power) result in cooling of the reactor. Thus, when the cooling (in fact due to the steam valve being jammed open) is detected, the crew attributes it to the previous actions of the shift supervisor (subjective probabilistic reasoning—CT4—).

The external event that would have enabled the crew to change the diagnosis is detection of the problem with the steam valve. The crew expects the valve to close at the end of the test (PSF1), but the 'closure' limit switch light does not light up (PSF2). The crew knows that limit switch problems have been detected before and that maintenance is scheduled (PSF3). So they think that the information given on the mimic diagram is erroneous (subjective probabilistic reasoning); they check that the closure signal has indeed been sent to the valve (PSF4) and make no further search, since their assumption is validated (fixation on the initial diagnosis). The crew therefore sticks to its initial diagnosis on the cause of cooling.

4.2.3.3 Example 3: (Incident #1) Inhibition of SI (safety injection) when the first criterion appears (#**1.5**). Cognitive tendencies activated: 'reluctance to undertake unusual actions or actions with negative consequences'—CT2—and 'fixation'—CT3—of Table 3.

The crew sticks to a cause (fixation on the initial diagnosis—CT3—) that explains the cooling and think they can act on the effects (reduction of AFWS flow for example). The crew therefore feels it has the situation under control (PSF1). But they are under a strong time constraint (PSF2). Whence their reluctance to let the situation deteriorate by letting the SI—which is deemed needless—start.

4.2.3.4 Example 4: (Incident #1) Inhibition of SI (safety injection) when the second criterion appears (#**1.6**). Cognitive tendency activated: 'reluctance to undertake unusual actions or actions with negative consequences'—CT2—and 'fixation'—CT3—of Table 3.

Following the logic of the preceding actions (fixation—CT3), the crew takes in hand the normal operation procedure (situation under control, with no incident, as the operators see it) covering the situation and which will provide after-the-event justification of the actions taken—control of cooling and inhibition of SI. By following the procedure, SI is inhibited when the second criterion appears.

The factors involved in the decision are the same as those in example 3. The additional factor that makes this situation different is the crew's determination to be able to provide subsequent justification of their actions by using a procedure—a behavior that is induced by the organization of power plants (need for justification of operator actions during incident analysis carried out afterwards).

Since cooling is still occurring despite the actions taken, the crew realizes that the situation is not under control; the diagnosis is then questioned, additional information is sought (steam consumption figures), the break is detected, and corrective action is taken.

4.2.3.5 Example 5 (Incident #2). For occurrences #2.2 (continuation of pressure increase) and #2.3 (failure to reduce pressure) a plausible causal factor becomes visible by a holistic view of the underlying sequence of events, e.g. related to the context of #2.3: detection of erroneously open valve → closure of valve.

These two actions are closely related. Thus, the required action (reducing pressure) between them is likely to be omitted. We would denote the underlying cognitive tendency as 'fixation' on a sequence of closely related actions (CT3). Moreover, we consider that incident #3 most probably illustrates 'eagerness to act'—CT1—(occurrence #3.2) and 'reluctance'—CT2—(occurrence #3.4), but we do not detail the analysis here.

4.3 Literature review of cognitive tendencies and linking to observed phenomena

Various theories have been published concerning decision making. This literature review will be focused on decision theory, which provides very useful insights for our research about cognitive tendencies.

Most managers and system designers of industrial installations used to assume that operator decision-making was rational in the sense of objective optimization. They expected the operators to optimize the expected objective values of the various uncertain outcomes for a decision problem. Psychology recognized that humans do not behave as rationally as expected [67,68]. Many laboratory experiments have been carried out to investigate the structural deviations from rational decision-making. It is recognized that such deviations should not always be interpreted as 'human errors'. These 'irrational' behaviors could also result in superior outcomes for practical situations [69]!

A well-known and generally accepted insight from cognitive psychology is that human decision-making is not simply driven by the objective values of the possible outcomes, but more by the subjective values that the decision-maker attributes to these outcomes. These subjective values are called 'utilities'. In the utility of an outcome, the individual 'feelings and attitudes' of human operators play a major role, and the utility to be optimized is often a subjective compromise of several goals. Furthermore, because exact probabilities for how a decision turns out are not available for so-called ill-defined problems [70], which reflect most realistic situations, the human operator has to make a subjective judgement about the likelihoods of the possible outcomes. These two aspects resulted in the subjective expected utility (SEU) model for human decision-making [71]. Four basic premises underlie this model:

1. The complete collection of all choice alternatives is available.
2. A well-defined utility function for the possible outcomes is available, with all utilities in one dimension.
3. A (subjective) probability can be attributed to all possible outcomes.
4. The goal of the decision is to maximize the subjective expected utility.

Obviously, this model only describes realistic human decision-making for the ideal decision-maker in an ideal situation. The limitations of the SEU model as a descriptive model for human decision-making became increasingly clear in the 1950s. People proved to not always maximize the outcome of their choices. Simon [67] draws attention to two basic problems:

1. *Bounded rationality*: there is a presumed limited capacity of human information-processing.
2. *Search problem*: in realistic situations, not all choice alternatives for a decision-problem are available. It takes time and effort to search for additional alternatives.

Both basic problems introduce a variety of cognitive tendencies that will be described later in this section.

In the 1970s, another more psychological approach to the restrictions of the SEU model was followed. The main setting for this comes from Tversky and Kahneman [68]. They believe that bounded rationality is not only due to a capacity limitation, but more to inherent cognitive mechanisms, called heuristics. The three main heuristics they propose are:

1. *Representativity*: people tend to neglect certain statistical information that is important for the probability judgement.
2. *Availability*: the selection and use of information or solutions depends on how easily available it is.
3. *Adjustment and anchoring*: people adjust their estimates insufficiently, considering the information contents of subsequent data. This adjustment heuristic results in a tendency to hold on to the initial idea (anchoring).

These three heuristics comprise a whole variety of cognitive tendencies as well.

Tversky and Kahneman [72] also presented the prospect theory, which is a special version of the utility function. Here, the utility of an outcome is not related to the absolute possession it represents, but to the change in possession in which the outcome will result. For profit situations the function is concave and less than linear, for loss situations it is convex but initially more than linear. Such presumed non-linearities of the utility function are the basis for several other cognitive tendencies.

Besides the cognitive tendencies that are based on decision-theory, various deviations from rational behavior have become apparent from the attribution-theory research. Furthermore, during the literature review, several other cognitive tendencies were found that were not directly connected to decision-theory or attribution-theory.

All cognitive tendencies that were found in the literature review are presented in Table 5. This listing by no means represents a fixed classification, but it is merely arranged according to the discussion above. There are undoubtedly more cognitive tendencies than those presented in Table 5. Furthermore, there are many other descriptions and names for the same or almost the same phenomena. These reservations make this listing no more than a subjective reproduction of a limited number of cognitive tendencies. Nevertheless, it is expected to provide some kind of overview.

Table 5. Overview of cognitive tendencies. The descriptions of the CT presented here are not really sufficient for a full understanding. For more information the reader is referred to the references indicated. Most of these references are not the original sources for the phenomenon, but are literature reviews themselves

Cognitive tendency	Description	References
Bounded rationality	limited capacity of human cognition. Complex problems are simplified, or even over-simplified	67
limit cognitive strain	minimize the cognitive effort allocated to a task (in order to keep capacity available for unexpected events)	73
insufficient consideration of processes in time	people have difficulties in dealing with system dynamics. People have only limited attention for information that is subject to delayed feedback	74,12,73
think in single orderings, instead of separate orderings (Halo-effect)	people tend to think in causal series, not in causal nets	74,12
polarization of thinking	people tend to attribute events to one global cause, instead of the combination of causes	75
thematic vagabonding	jump from one alternative to another, treating each of them very superficially	12
people seek more info than they can absorb adequately	—	73
encystment	small details are attended to while other, more important issues are disregarded	74,76,12
Search problem	in realistic situations, not all choice alternatives for a decision problem are available	67
satisfying	the search for additional alternatives will be adjourned if one of the alternatives exceeds the minimal desired level of SEU. People tend to settle for satisfactory, rather than optimal solutions	67,12
conclusion jumping (hypervigilance)	fail to see all alternatives that are open, where the most available alternative is selected, irrespective of its appropriateness	12,77
elimination by salient aspects	no adequate comparison of all alternatives in parallel	78 in 73
confirmation bias (hypothesis anchoring)	people tend to search for verification, instead of falsification	12
tunnel vision (selective feedback; expectation bias)	people tend to concentrate only on the information that is related to their prevailing hypothesis, neglecting other important information. People give too much weight to information that supports their predictions	77
hypothesis fixation (cognitive lockup, mind set)	people hold on to their initial hypothesis, even in the light of falsificating evidence. People tend to focus on single, initial faults, ignoring other tasks	12,79
Representativity	'like causes like', indicating that people tend to judge causality on the basis of perceived similarities, neglecting statistical evidence for such a causal relationship	68
base rate fallacy	neglect a priori probabilities	68
neglect sample size	—	68
gamblers' fallacy	misconceptions of chance, where people for instance presume that a coin has a memory. Poor performance for estimating randomness of data	68
neglect statistical predictability; too extreme predictions	people tend to overpredict and are insufficiently regressive in their predictions. Overconfidence in their forecasting	68,73,79
conjunction fallacy	people sometimes estimate that the probability that event 'A plus B' is true is higher than the smallest probability of one of the separate events	69,73
illicit conversion of premises (or, bidirectional inference bias)	people often assume that the probability that A will cause B is the same as the probability that B was caused by A. Incorrect testing of a conditional rule	80,73,79
estimation of variance	estimation of variance is led by two most extreme values, ignoring the dispersion of other data points. The estimation is smaller when the mean of the quantity is larger	69,73
treat all information as being equally reliable, even though it is not	—	69,73
illusory validity (atmospheric effect)	if a causal relationship between events is expected a priori, the correlation is overestimated a posteriori	81,69

Table 5. (continued)

Cognitive tendency	Description	References
Availability	the selection and use of information depends on the ease of availability of information. More easily available information is given higher probabilities of occurrence	68
familiarity	more familiar information is given too much weight in the attribution of probabilities to events	68
imaginability (capture effects)	more imaginable information is given too much weight. The imaginability is related to the effectiveness of a memory search set	68
recency	events that happened recently are recalled more easily than events that occurred a long time ago	12
frequency	events that occur frequently are recalled more easily than scarce events	12
degree of previous achievement (success or not)	previously successful alternatives are selected more easily than unsuccessful alternatives, even when not adequate for the current situation	12
strong habit intrusions (stereotype takeover)	aspects of a strong action sequence may interfere with the desired, but less strong, action sequence	12,77
stereotype fixation (inert stereotype, strong-but-wrong schemata)	the desired action sequence is entirely superseded by a more available (strong) sequence	12,77
out of sight, out of mind	people make insufficient use of the absence of particular information	12,73
sampling bias (shift of attention)	people allocate more attention to information sources with recent or frequent variations	73
cheapskate mentality	people prefer to purchase 'cheap', unreliable information over more 'expensive', but reliable information. 'Cheap' and 'expensive' is related to the difficulty to obtain the information or to the difficulty to interpret and understand it.	82
hindsight bias	if a rare event is observed a posteriori, the a priori probability of occurrence is overestimated. Tendency to 'be wise after the accident'	12,73
illusory correlation	in the recognition of a relationship between observed events, people tend to overestimate the correlation. This accounts for striking, rare events	81,69
Anchoring	with more information that comes available, the final estimated value tends towards the first estimate. Improper calibration	68
overestimate probability of conjunctive events	conjunctive: e.g., drawing a red marble seven times in succession	68
underestimate probability of disjunctive events	disjunctive: e.g., drawing a red marble at least once in seven successive tries	68
Adjustment	people adjust their estimates insufficiently, considering the information contents of subsequent data	68
conservatism (primacy, dwelling in the past)	new, additional information is judged to be less informative	76,73
increased, but unjust confidence, with more information	with additional but redundant information, people become more confident in their decision	73
Framing (level effect)	the decision depends on whether the same problem is formulated in terms of profits or in terms of losses	72
risk-searching behaviour in loss situations	when formulated in terms of losses: people tend to prefer an uncertain but high loss, over a certain but low loss (expected value is the same)	72
risk-avoiding behaviour in profit situations ('take the money and run')	when formulated in terms of profits: people tend to prefer a certain but low gain, over an uncertain but high gain (expected value is the same)	72
increased risk-searching when previous failure has occurred	—	
loss aversion (err on the safe side)	people tend to prefer certain costs over an uncertain but very high loss (take out insurance)	73

Table 5. (continued)

Cognitive tendency	Description	References
Value bias	the estimation of the likelihood depends on the value of the outcome	83
reliance on positive hits	people tend to overestimate their likelihood of success if they desire the outcome (play the lottery)	83,79
defensive avoidance	people tend to underestimate the likelihood of undesired outcomes	76
Central tendency bias (avoid extreme values)	people tend to avoid extreme values. They tend to the mean value	84
small probabilities are over-estimated	—	84,73
high probabilities are under-estimated	—	84,73
conservatism in extrapolation	people tend to extrapolate more than linear functions towards linearity	73
Fundamental attribution error (overattribution)	people tend to underestimate situational factors and overestimate personal factors (if it does not involve themselves)	69
exculpation tendency	people tend to search for external reasons for their failure, rather than blaming themselves for it	69
Egocentric biases	biases based on motivational and self-protective arguments	69
self-centred bias	one's own judgement is centralized as being the most important one	69
false consensus bias	the feeling that 'if I react in that way, everybody will react in that way'	69
reinforced group conformity (groupthink syndrome)	pressure on members of a group to agree with the general idea of the group	85,77
self-serving bias	risk is estimated lower when it affects yourself than when it affects others	69
illusion of control, personal role bias	people tend to overestimate their control over risky situations. People tend to over-control a situation and are overconfident in their own abilities	73,83
delegate risky decisions	if there are major negative potential consequences involved, people tend to delegate decisions to others. They do not want to be responsible for major losses	73
increased risk-taking in groups	the possibility of shifting the blame to somebody else leads to an increased risk-taking in groups (shared responsibility)	83
Others		
emotional biases	in depressive moods the probability of failure is estimated to be higher	83
too much weight on immediate consequences	immediate adverse consequences are considered more important than delayed, more serious consequences	73
difficulties in dealing with reliability concepts	people tend to flip over from complete trust to complete distrust. Tendency to ignore less reliable information	73
risk homeostasis. Violate extensive and detailed rules	people tend to maintain a certain level of risk (disputed concept)	77
voluntary or familiar risks are rated lower	if an activity is regarded as less voluntary, less personally controllable, or less familiar, its riskiness is rated higher	86

Many cognitive tendencies have different manifestations, and they are often highly interdependent. There are several tendencies that are seemingly contradictory. This may illustrate that the interpretation of cognitive tendencies depends highly on the specific circumstances as was pointed out in Section 4.2. Therefore, a context-free listing of cognitive tendencies such as in Table 5 may only serve as an initial reference listing. Table 6 tries to put some 'flesh' on the rather abstract cognitive tendencies from the reference listing, by assigning the cognitive tendencies observed from the three incident analyses in Section 4.2.

The assignment of cognitive tendencies from the reference list to practical observations is not always straightforward. One of the reasons for this is the lack of a theory about cognitive tendencies that would help to structure and classify them in a more transparent manner. Current knowledge on cognitive tendencies is fairly incomplete and more research is needed. It is presumed by the EARTH working

Table 6. Assigning observed cognitive tendencies to cognitive tendencies from literature

CT observed in nuclear power plants from Table 3	Literature CT from the reference list in Table 5
(CT1) Eagerness to act (to reduce stress, to get a margin and reduce time constraints)	—Limit cognitive strain minimizing the cognitive effort allocated to a task, in order to keep capacity available for unexpected events [73]
(CT2) Reluctance to undertake unusual actions or actions with negative consequences	—Risk-searching behavior in loss situations (people tend to prefer an uncertain but high loss over a certain but low loss) [72] —Too much weight on immediate adverse consequences (they are considered to be more important than delayed, more serious consequences) [73] —Voluntary or familiar risks are rated lower [86]
(CT3) Fixation	—Confirmation bias, hypothesis anchoring (people tend to search for verification instead of falsification) [12] —Hypothesis fixation (cognitive lock-up) [12] —Tunnel vision (selective feedback; expectation bias) [77] —Cheapskate mentality (people prefer 'cheap'—easy to obtain—but unreliable information over more 'expensive' but reliable information) [82]
(CT4) Subjective probabilistic reasoning	—Familiarity, imaginability (more familiar or imaginable information is given too much weight in the attribution of probabilities to events) [72] —Reliance on positive hits (people tend to overestimate their likelihood of success if they desire the outcome) [79] —Defensive avoidance (people tend to underestimate the likelihood of undesired outcomes) [76] —Voluntary or familiar risks are rated lower [86] —Too much weight on immediate adverse consequences [73]

group that at this moment much can be learnt from practical situations. This section shows how it may be investigated whether a cognitive tendency from literature has a practical value for HRA application in industrial installations.

4.4 How should cognitive tendencies be used in human reliability analysis?

Examination of the cognitive tendencies observed in nuclear power plants shows that they are in fact linked to the operators' *search for efficiency. Operators tend to set up the best possible trade-offs* between the various constraints and objectives (especially safety/production trade-offs). It seems that, to do so, they often adopt psychic and material 'cost' minimization strategies (material 'costs': loss of production, damage to equipment, etc.). Anticipation of actions (linked to tendency CT1, 'eagerness to act') and 'fixation' (CT3) enable a decrease of emotional load (stress) and work load (cognitive or physical). The tendency to avoid the actions which penalize equipment or production (CT2) has a real economic interest. Lastly, the use of probabilistic reasoning concerns both material and psychic levels at the same time.

From this analysis it can be deduced that cognitive tendencies are not themselves mechanisms of error. They generally refer to adaptive mechanisms that play a positive part most of the time. *Should these cognitive tendencies not exist, the operators would have great difficulty doing their work.* But these optimization strategies are not perfect. They are affected by some quite general biases that are mentioned in the literature (cf. Section 4.3). In addition, they cannot be entirely suitable for all situations (in fact they are essentially developed and implemented for normal or only slightly disturbed situations). Consequently, in certain cases—and especially in incident or accident situations—they can be a source of failure. The 'situation factors' and 'elements in operators' interpretation' associated with each tendency in Table 3 set out to define some of the more important aspects of these situations where tendencies are inappropriate.

To use cognitive tendencies in HRA, one could therefore investigate to see if, for each accident sequence studied, certain 'situation factors' and 'elements' can be found in this situation. Thus, for example, if, during an accident sequence, operators have to wait unoccupied before initiating an important action, then the risk of failure is rather high, because of the operators' eagerness to act in such a situation, *unless other factors compensate this tendency.*

For the factors do interfere. Human behavior is very complex. We cannot apply the proposed method mechanically. Experience is required, and in order to understand the phenomena properly, practice in detailed analysis of real and simulated cases is essential. So the method anticipated *will not prevent making a deep analysis of the context to which it is applied* [28]. Such an analysis will be necessary to 'update' cognitive tendencies in accordance with the real context. The purpose is—through on-site observations, interviews and simulations—to analyze how these tendencies appear concretely in the specific operator population studied. Current practices and attitudes may vary significantly from one company to another and even from one NPP to another. Moreover, when cognitive tendencies have been updated, field information will be necessary to track error-prone situations by looking for 'situation factors' and 'elements'.

5 DECISION-BASED UNREQUIRED ACTIONS IN HUMAN RELIABILITY ANALYSIS: WHERE TO GO?

5.1 Cognitive tendencies for decision-based unrequired actions

Our experience has shown us that operators' practices and attitudes under *normal* operation still strongly influence their actions under *abnormal* situations. This led us to the assumption that better knowledge of these current practices could notably improve HRA and in particular the forecasting of DUA. Besides, this assumption is totally consistent with the use of a human-centered model that emphasizes operator's active part in transforming conditions through the signification he ascribes to them. It is also consistent with the introduction of the 'safety culture' concept in the nuclear industry, since Chernobyl.

To verify this assumption, the EARTH group has studied opportunities for using the notion of 'cognitive tendency'. This notion, voluntarily kept general in this exploratory phase, integrates the characteristics of practices and attitudes.

Relying on our experience and on incident analysis, we have proposed examples of NPP operators' cognitive tendencies. An analysis of literature has shown that these examples can be connected to cognitive tendencies proposed by various theories. Thus, there are some theories, or, at least, laboratory data, that enable the trend proposed to be enriched and structured. In the end, indications have been given on the way the notion of cognitive tendency could be used in HRA, in a practical manner.

This exploratory study seems to confirm the original assumption: better knowledge of the operators' cognitive tendencies would be useful in HRA. There are two conditions:

1. we remain aware of the complexity of the phenomena, of the interaction of various factors;
2. we use the notion of cognitive tendency to guide the collection of the on-site information, the description of context, and the search for hazardous conditions. In other words, we do not offer an approach that would relieve the HRA specialist of a serious on-site contact, and that would supply him with 'predictive' tools 'mechanically'.

The method outlined may be of benefit not only to DUA analysis but also to the study of other kinds of decision-making (e.g. omissions or recoveries). It also seems that there could be other applications outside the field of HRA, as long as it is useful to establish a 'prediction' of the unexpected decisions operators may take. This can be the case, for example, for an ergonomic design, in the absence of a systematic HRA study.

If there is something new, it is not in the notions introduced, but rather in the idea of applying them more systematically to HRA and in the illustration supplied by real or simulated cases and by the literature. In our investigations we saw that without an appropriate context description, it is very difficult to interpret cognitive tendencies. We think that linking current knowledge of cognitive tendencies with the real context of operational activities is a valuable step in the advancement of HRA methods.

5.2 Probabilities for decision-based unrequired actions

This was an exploratory study, a study to obtain a better view of the qualitative mechanisms that underlie human behavior in case of DUA. Of course, when we talk about HRA there is also the quantitative part: the quantitative assessment of probabilities, an effort that has up to now always been the major controversial feature. Should we indeed try to assess an absolute number for such events as DUA?

The first attempts to assess human error probabilities stem from applying the mechanist approach for reliability assessment of technical systems to humans. These first attempts for simple human activities seemed not to be that wrong. If decision-making plays a minor role, it is less difficult to identify potential human errors and assess their probability of occurrence. In this case, where a fixed strategy is followed, the desired activities can be defined explicitly, and the potential human errors can be identified and subsequently assigned numbers. The mechanistic techniques (e.g. event trees which are so successfully applied in PRA) are reasonably applicable to humans if a number of particular human characteristics are taken into account, e.g. the aspect of recovery, dependencies between human activities, etc. [87].

It is, however, entirely different for decision-based behavior, i.e. knowledge-based behavior in terms of [88]. An essential aspect of knowledge-based behavior is that problem solving behavior is involved, in which the human operator has to determine a strategy to be followed. In fact, this is the main reason why we have humans in a complex process. A design can never be so perfect that all possible events can be foreseen. A human operator in a process should be able to diagnose an unforeseen event and take corrective actions.

All this holds in particular for complex modern processes where consequences of failures are severe (e.g. in NPP). Owing to these consequences, we try to make the processes as reliable as possible. The result is that we are less able to learn from all kinds of undesired events. This is very important in current complex and highly automated systems where diagnostic, problem solving behavior and DUA may be more crucial [89].

In our exploratory study we have focused on using cognitive tendencies to model problem-solving behavior, which in our view contributes to the possibility of predicting DUA. This applies to problem-solving behavior for which strategies are reasonably well known and can be practised in simulators. It is this kind of knowledge-based behavior for which probabilities may be obtained and psychological science helps us to understand better the relationship between context and cognition.

A critical note on this application should, however, be given. There may be certain complex events for which operators' strategies may be entirely unclear. Such phenomena defy description, and, therefore, it is impossible to analyse them. This marks the limit of error identification and quantification.

Also, the application of detailed models is then questionable. In applying analytic thought—the knife—as is definitely the case in applying detailed models, something may die [90]. This may well be that part of the context that played an essential role. The use of models implying no detailed decomposition but taking human behavior as a whole might be applied. Cognitive tendencies as basic preferences for types of behavior may form the fundamentals of such models.

Do these comments mean that we should not quantify DUA in the case of problem-solving behavior for which the strategies to be followed are unclear? We should do it to obtain a feeling for the contribution of human error to safety (see Sträter [54]). However, such numbers cannot be derived from experience. It is not possible to reproduce these situations identically in order to calculate probabilities. Thus, we should not talk about a probability that expresses a number of errors divided by a number of opportunities, but about a *likelihood* that expresses the analyst's judgment about the relative chance of occurrence.

A likelihood, expressing the analyst's feeling about the relative chance that a person (or a group) may function incorrectly, may be the only believable number for certain DUA. An important way to improve these assessments is to continue to gather cases and discover which cognitive tendencies played a role in the DUA that took place. *Naturalistic inquiries* of the context are essential when we talk about humans [62]. This is not only important from a retrospective point of view. Going into the field and meeting future users is important to gain an understanding of cognitive tendencies, preferences for behavior, that may be the basis of DUA causing disasters.

5.3 And now?

This was an exploratory study. We still have to carry on with the recording of cognitive tendencies and specifying them as far as possible according to the context where they occurred. We should better define the terms used, and better structure cognitive tendencies, e.g. in the light of literature. In particular, the terms 'cognitive tendency' and 'attitude' may be too general. We should of course define more accurate categories. A more comprehensive assessment of the proposed ideas, in the light of literature (e.g. of the latest works in HRA and in cognitive sciences—such as Varela [91]), and by practical implementations in HRA studies, is also needed.

Like HRA, the methods of ergonomic design have a predictive goal. They aim at qualitative forecasting of the operators' future activity on the system under design. There are similarities with HRA [44], but the links between the two types of methods could be strengthened [92]. Our proposals about a human-centered model, cognitive tendencies, on-site information collection may be a step in this direction. A critical comparison would therefore be very interesting.

REFERENCES

1. Swain, A. D. & Guttmann, H. E., Handbook of human reliability analysis with emphasis on nuclear power plant applications. Final report. *NUREG/CR-1278*, USNRC, Washington, DC, 1983.
2. NRC, *Engineering Evaluation — Operating Events with Inappropriate Bypass or Defeat of Engineered Safety Features*. Office of Analysis and Evaluation of Operational Data, US NRC, Washington, DC, 1995.
3. IRS, *IRS Kurzinformationen. Kernkraftwerk Obrigheim, Bersten eines Entwässerungsbehälters durch Kühlmittelverlust über das Entwässerungssystem.* Institut für Reaktorsicherheit der Technischen Überwachungsvereine (IRS), Köln, 1972.
4. BMI, *Besondere Vorfälle in Kernkraftwerken der Bundesrepublik Deutschland. Berichtszeitraum: 1965–1976.* Der Bundesminister des Innern, Bonn, 1977.
5. Hoffmeister, N., Analyse einiger wichtiger Vorkommnisse in Kernkraftwerken. In *Proceedings of the Informationstagung über die Sicherheit von Kernkraftwerken, 25./26. November 1974*, Tagungsreferate. Schweizerische Vereinigung für Atomenergie (SVA), Bern, 1975.
6. Smidt, D., *Reaktorsicherheitstechnik*. Springer, Berlin, 1979.
7. Kemeny, S. G., *Report of the President's Commission on the Accident at Three Mile Island.* U.S. Government Printing Office, Washington, DC, 1979.
8. Pew, R. W., Miller, D. C. & Feeher, C. E., Evaluation of proposed control room improvements through analysis of critical operator decisions. *EPRI-NP-1082*, Electric Power Research Institute, Palo Alto, CA, 1981.
9. NRC, Loss of main and auxiliary feed water event at the Davis-Besse Plant on June 9, 1985. *NUREG-1154*, USNRC, Washington, DC, 1985.
10. BMU, *Übersicht über besondere Vorkommnisse in Kernkraftwerken der Bundesrepublik Deutschland für das Jahr 1987.* Der Bundesminister für Umwelt, Naturschutz und Reaktorsicherheit, Bonn, 1987.
11. Embrey, D. E. & Reason, J. T., The application of cognitive models to the evaluation and prediction of human reliability. In *Proceedings of the International Meeting on Advances in Human Factors in Nuclear Power Systems*, Knoxville, 21–24 April 1986, American Nuclear Society, La Grange Park, 1986, pp. 293–301.
12. Reason, J., *Human Error*. Cambridge University Press, Cambridge, 1990.
13. IAEA, *Human Reliability Analysis in Probabilistic Safety Assessment for Nuclear Power Plants, A Safety Practice, IAEA Safety Series* No. 50-P-10. International Atomic Energy Agency, Vienna, 1995.
14. Swain, A. D., Accident sequence evaluation program human reliability analysis procedure. *NUREG/CR-4772*, USNRC, Washington, DC, 1987.
15. Hannaman, G. W., Spurgin, A. J. & Lukic, Y., A model for assessing human cognitive reliability in PRA studies. In *Proceedings of the IEEE Third Conference on Human Factors in Nuclear Power Plants*, Monterey, CA, 23–27 June 1985, Institute of Electronic and Electrical Engineers, New York, 1985, pp. 343–353.
16. Williams, J. C., A data-based method for assessing and reducing human error to improve operational performance.

In *Proceedings of the IEEE 4th Conference on Human Factors in Power Plants*, Monterey, CA, 6–9 June 1988, Institute of Electronic and Electrical Engineers, New York, 1988, pp. 436–450.

17. Embrey, D. E., Humphreys, P., Rosa, E. A., Kirwan, B. & Rea, K., SLIM-MAUD: an approach to assessing human error probabilities using structured expert judgement, Vol. I: overview of SLIM-MAUD, Vol. II: detailed analyses of the technical issues. *NUREG/CR-3518*, USNRC, Washington, DC, 1984.
18. Potash, L. M., Stewart, M., Dietz, P. E., Lewis, C. M. & Dougherty, E. M. Jr, Experience in integrating the operator contributions in the PRA in actual operating plants. In *Proceedings of the ANS/ENS Topical Meeting on Probabilistic Risk Assessment*, Port Chester, NY, September 1981, American Nuclear Society, LaGrange Park, 1981, pp. 1054–1063.
19. Montmollin (de), M., Analysis and models of operators' activities in complex natural life environments. In *Human Computer Interaction*, eds J. Rasmussen, H. B. Anderson & N. O. Bernson. Lawrence Erlbaum, Hove, 1991.
20. Montmollin (de), M., Activity-oriented ergonomics. In *Work Activity Analysis in the Perspective of Organization and Design*. Université Paris Nord and EDF, Paris, 1992.
21. Mosneron Dupin, F., Saliou, G. & Lars, F., Probabilistic human reliability analysis: the lessons derived from plant operation at Electricité de France. In *Use of Probabilistic Safety Assessment for Operational Safety. PSA '91. Proceedings of an International Symposium*, Vienna, 3–7 June 1991, IAEA-SM-321/57, International Atomic Energy Agency, Vienna, 1992, pp. 625–638.
22. Reer, B., Entscheidungsfehler des Betriebspersonals von Kernkraftwerken als Objekt probabilistischer Risikoanalysen. *Berichte des Forschungszentrums Jülich; 2811*, KFA, Jül-2811, Jülich, 1993.
23. Sabri, Z. A., Husseiny, A. A. & Casto, W., Assessment of human contributions to significant trends based on LWR past operating experience. In *Proceedings of the ANS/ENS Topical Meeting on Probabilistic Risk Assessment*, Port Chester, NY, September 1981, American Nuclear Society, La Grange Park, 1981.
24. Swain, A. D., *Comparative Evaluation of Methods for Human Reliability Analysis*. GRS-71, Gesellschaft für Reaktorsicherheit (GRS) mbH, Köln, Garching, 1989.
25. Woods, D. D., Roth, E. & Pople jr, H. Modelling human intention formation for human reliability assessment. *Reliability Engineering and System Safety*, 1988, **22,** 169–200.
26. Woods, D. D., Roth, E. & Pople, H. Jr, The cognitive environment simulation as a tool for modeling human performance. *Main Report, NUREG/CR-5213*, Vol. 2. USNRC, Washington, DC, 1990.
27. Mosneron Dupin, F., Villemeur, A. & Moroni, J. M., Paluel nuclear power plant PSA: methodology for assessing human reliability. In *Proceedings of the 7th International Conference on Reliability and Maintainability*, Brest, June 1990, CNET, Lannion, France, 1990, pp. 584–590.
28. Mosneron Dupin, F., Is probabilistic human reliability analysis possible? In *Proceedings of the PSA and HRA Meeting*, Paris, 21–23 November 1994, IAEA-PC-3580, Vienna, 1996, Topic 6.
29. Moieni, P., Spurgin, J. & Singh, A. Advances in human reliability analysis methodology. part I: frameworks, models and data. *Reliability Engineering and System Safety*, 1994, **44,** 27–55.
30. Gertman, D. I., Blackman. H. S., Haney, L. N., Seidler, K. S. & Hahn, H. A. INTENT: a method for estimating human error probabilities for decision based errors. *Reliability Engineering and System Safety*, 1992, **35,** 127–136.
31. Gertman, D. I. & Blackman, H. S., *Human Reliability and Safety Analysis Data Handbook*. Wiley Interscience, New York, 1994.
32. Reer, B., Sträter, O. & Mertens, J., Evaluation of human reliability analysis methods addressing cognitive error modelling and quantification. *Berichte des Forschungszentrums Jülich; 3222*, KFA, Jül-3222, Jülich, 1996.
33. Barriere, M. T., Luckas, W. T., Cooper, S. E., Wreathall, J., Bley, D. C., Ramey-Smith, A. & Thompson, C. M. , Multidisciplinary framework for analyzing errors of commission and dependencies in human reliability analysis. NUREG/CR-6265 (Draft), USNRC, Washington, DC, 1994.
34. Cooper, S. E., Ramey-Smith, A. M., Wreathall, J., Parry, G. W., Bley, D. C., Luckas, W. J., Taylor, J. H. & Barriere, M. T., A technique for human error analysis (ATHEANA). Technical basis and methodology description. *NUREG/CR-6350*, USNRC, Washington, DC, 1996.
35. Julius, J., Jorgenson, E., Parry, G. W. & Mosleh, A. M. A procedure for the analysis of errors of commission in a probabilistic safety assessment of a nuclear power plant at full power. *Reliability Engineering and System Safety*, 1995, **50,** 198–201.
36. Hollnagel, E. Reliability analysis and operator modeling. *Reliability Engineering and System Safety*, 1996, **52,** 327–337.
37. Reer, B., Incorporation of risk-taking behaviour into human reliability analysis. In *Proceedings of the International Meeting: PSA/PRA and Severe Accidents '94*. Nuclear Society of Slowenia, Ljubljana, 1994.
38. EDF, EPS 1300. Probabilistic safety assessment of reactor unit 3 in the Paluel Nuclear Power Centre (1300 MWE). *Overall Report*. Electricité de France, Paris, 1990.
39. Sträter, O., Beurteilung der menschlichen Zuverlässigkeit auf der Basis von Betriebserfahrungen. Dissertation, Technical University of Munich, Munich, 1996.
40. Gerdes, V., Method to identify and analyse cognitive errors, for control room operators in complex industrial installations. Thesis, Delft University of Technology, by order of N.V. KEMA, BU-PCL, Arnhem, 1996.
41. Ullwer, W., Simulatorinformationen als Instrument zur realitätsnahen Modellierung von Personalhandlungen in PSA (working title). Dissertation, Jülich, 1997.
42. Gerdes, V., Towards a method to analyze cognitive errors during accident management: a taxonomy of cognitive errors. In *Proceedings of the XII European Annual Conference on Human Decision Making and Manual Control*, Espoo, Finland, 13–14 June 1994.
43. Gerdes, V., Method to identify cognitive errors during accident management tasks. In *Proceedings of the 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man–Machine Systems*, MIT, Cambridge, MA, 27–29 June 1995.
44. Sträter, O., A connectionism approach for assessing the reliability of human actions, a program for the evaluation of plant experience. Paper presented at the Enlarged Halden Reactor Project Group Meeting, Gol, Norway, 1993.
45. Sträter, O., Eine Methode zur Erfassung und Auswertung von Betriebserfahrung im Hinblick auf menschliche Fehler. In *Technische Zuverlässigkeit. Tagung Fulda*. 26/27.9.1995. VDI-GSP, Düsseldorf, 1995.
46. Mehl, K., Ullwer, W., Mertens, J. & Reer, B., Simulation—ein geeigneter Zugang zur differenzierten Analyse menschlicher Zuverlässigkeit. In *1. Berliner Werkstatt Mensch–Maschine-Systeme, Verläßlichkeit von Mensch–Maschine-Systemen*, Berlin, 1995.
47. Wilpert, B., Fank, M., Becker, G., Fahlbruch, B., Freitag, M., Giesa, H.-G. & Miller, R., Weiterentwicklung der Erfassung und Auswertung von meldepflichtigen Vorkommnissen und

sonstigen registrierten Ereignissen beim Betrieb von Kernkraftwerken hinsichtlich menschlichen Fehlverhaltens. *SR 2039/1*, Der Bundesminister für Umwelt, Naturschutz und Reaktorsicherheit, 1994.

48. IAEA, ASSET guideline, Revised 1991. *IAEA-TECDOC-632*, Vienna, 1991.
49. Okrent, D. & Xiong, Y., Safety culture evaluation and ASSET root cause analysis. In *Proceedings of the International Topical Meeting on Safety Culture in Nuclear Installations*, Vienna, 24–28 April 1995, ANS Austria Local Section, Vienna, 1995.
50. IAEA, IAEA Technical Committee Meeting on Review of Experience with Root Cause Analysis, Vienna, 1993.
51. SVA (Ed.), *SVA-Ausbildungsseminar (Workshop), Ursachenanalyse von Störfällen in Kernkraftwerken, 3./4. März, H öhere Technische Lehranstalt (HTL), Brugg-Windisch, Windisch, Seminarreferate*. Schweizerische Vereinigung für Atomenergie (SVA), Bern, 1994.
52. Harbour, J. L. & Hill, S. G., *HSYS — A Methodology For Analyzing Human Performance in Operating Settings*. EG and G. Idaho, Idaho Falls, ID, 1991.
53. Sträter, O., A method for human reliability data collection and assessment. In *Proceedings of the International Conference on Probabilistic Safety Assessment and Management ESREL '96 — PSAM—III*, Springer, London, 1996, pp. 1179.
54. Sträter, O., Assessment of cognitive errors and organizational aspects based on evaluation of plant experience. In *Proceedings of the International Conference PSA '96*, Salt Lake City, September 1996, ANS, La Grange Park, 1996, pp. 245–ff.
55. EDF, *Guide d'analyse d'un événement — Application à la sûreté*, Indice 3. Electricité de France, Paris, 1994.
56. Reer, B., Guiding principles for retrospective analyses of safety-related events with emphasis on the human factor. Internal Report, KFA-ISR-IB-3/96, Jülich, 1996.
57. Wolters, J., Der Reaktor-Unfall im Kernkraftwerk Three Mile Island und seine Bedeutung für die Sicherheitstechnik. Interner Bericht, KFA-ISF-IB-3/79, Jülich, 1979.
58. Mertens, J. & Reer, B., Insights obtained from human reliability analyses for chemical processses and nuclear power plants. In *Proceedings of the Seminar/Workshop on Methodological Issues of Probabilistic Safety Analysis/ Human Reliability Analysis and Development of Supporting Software Tools*, Technical University of Gdansk, Gdansk, 1994.
59. Reer, B. & Mertens, J., Safety culture as an element of plant design for the reduction of risk from unsafe operator actions. In *Proceedings of the International Topical Meeting on Safety Culture in Nuclear Installations*, Vienna, 24–28 April, ANS Austria Local Section, Vienna, 1995.
60. Wustmann, R., Eine Auswertung des Verhaltens von Betriebspersonal bei realen Störfällen auf Fragestellungen in probabilistischen Analysen. Diplomarbeit, Interner Bericht, KFA-ISR-IB-8/95, Jülich, 1995.
61. Frederick, E. R., Design, training, operation: the critical links, an operator's perspective. In *Proceedings of the International Symposium on Severe Accidents in Nuclear Power Plants*, Sorrento, Italy, 21–25 March 1988, IAEA-SM-296/ 91, IAEA, Vienna, 1991, pp. 643–652.
62. Gubal, E. G. & Lincoln, Y. S., *Fourth Generation Evaluation*. Sage Publications, London, 1989.
63. Reer, B. & Sträter, O., Evaluation of new developments in cognitive error modeling and quantification: time reliability correlation. In *Proceedings of the International Conference on Probabilistic Safety Assessment and Management ESREL '96 — PSAM-III*, Springer, London, 1996, pp. 615.
64. IAEA, *Safety Culture. IAEA Safety Series* No. 75—INSAG 4. International Atomic Energy Agency, Vienna, 1991.
65. Davoudian, K., Wu, J.-S. & Apostolakis, G. Incorporating organizational factors into risk assessment through the analysis of work processes. *Reliability Engineering and System Safety*, 1994, **45**, 85–105.
66. Dougherty, E. M. Jr, Context and human reliability analysis. *Reliability Engineering and System Safety*, 1993, **41**, 25–47.
67. Simon, H. A. A behavioral model of rational choice. *Quarterly Journal of Economics*, 1955, **69**, 129–138.
68. Tversky, A. & Kahneman, D. Judgment under uncertainty: heuristics and biases. *Science*, 1974, **185**, 1124–1131.
69. Van Dam, K., *Fixatie op fouten. Kunnen mensen beslissen?* Swets and Zeitlinger, Lisse, 1991.
70. Sternberg, R. J. (ed.), *Human Abilities. An Information-Processing Approach.* Freeman, Basingstoke, 1985.
71. Neumann, J. von & Morgenstern, O., *A Theory of Games and Economic Behavior.* Princeton University Press, Princeton, 1944.
72. Tversky, A. & Kahneman, D. The framing of decisions and the psychology of choice. *Science*, 1981, **21**, 453–458.
73. Wickens, C. D., *Engineering Psychology and Human Performance.* Harper Collins, New York, 1992.
74. Dörner D., On the difficulties people have in dealing with complexity. In *New Technology and Human Error*, eds J. Rasmussen, K. Duncan & J. Leplat. John Wiley, Chichester, 1987.
75. Nisbett, R. & Ross, L., *Human Interference: Strategies and Shortcomings of Social Judgment.* Prentice-Hall, Englewood Cliffs, NJ, 1980.
76. Kontogiannis, T. & Lucas, D., Operator performance under high stress: An evaluation of cognitive modes, case studies and coutermeasures. *Report No. R90/03*, prepared for the Nuclear Power Engineering Test Center, Tokyo, Human Reliability Associates, Dalton, Wigan, Lancashire, UK, 1990.
77. CCPS, *Guidelines for Preventing Human Error in Process Safety.* Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York, 1994.
78. Payne, J. W., Information processing theory: some concepts and methods applied to decision research. In *Cognitive Processes in Choice and Decision Behavior*, ed. T.S. Wallsten. Erlbaum, Hillsdale, NJ, 1980.
79. Fraser, J. M., Smith, P. J. & Smith, J. W. A catalog of errors. *International Journal of Man–Machine Studies*, 1992, **37**(3), 265–307.
80. Thijs, W. L. T., Fault management. Thesis, Delft, TNO-IWECO, 1987.
81. Chapman, L. J. & Chapman, J. P. Illusory correlation as an obstacle to the use of valid psychodiagnostic signs. *Journal of Abnormal Psychology*, 1969, **74**, 193–204.
82. Kanarick, A. F., Huntington, A. & Peterson, R. C. Multi-source information acquisition with optimal stopping. *Human Factors*, 1969, **11**, 379–386.
83. Yates & Stone, in *The Psychology of Risk Taking Behavior*, ed. R. M. Trimpop. Elsevier Science, Amsterdam, 1994.
84. Wexley, K. N. & Yukl, G. A., *Organizational Behavior and Personnel Psychology.* Irwin, London, 1984.
85. Janis, I.L., *Victims of Groupthink.* Houghton Mifflin, Boston, 1972.
86. Hendrickx, L., How versus how often. The role of scenario information and frequentie information in risk judgement and risky decision making. Thesis, University of Groningen, 1991.
87. Heslinga G., Technique for human-error identification and signification. Ph.D. thesis, Delft University of Technology, The Netherlands, 1988.
88. Rasmussen J., Human error data. Facts or fiction? *Report Ris-M-2499*, Ris National Laboratory, Roskilde, Denmark, 1985.
89. Heslinga, G. & Herbert, M., Experiences with advanced

systems for human–machine interaction. In *Proceedings of the 6th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man–Machine Systems*, MIT, Cambridge, MA, 1995.

90. Pirsig, R. M., *Zen and the Art of Motorcycle Maintenance, an Inquiry into Values*. Corgi Books, Transworld, London, 1974.
91. Varela, F. J., *Invitation aux Sciences Cognitives*, 2e edn. Editions du Seuil, Paris, 1996 (also in English under the title *Cognitive Science. A Cartography of Current Ideas*).
92. Heslinga G., Assessment of human performance safety for supporting task allocation decisions. In *Proceedings of the International Symposium on 'Balancing Automation and Human Action in Nuclear Power Plants'*, Munich, 9–13 July 1990, IAEA Report, Vienna, 1991.

APPENDIX A SOME DETAILS OF DERIVING COGNITIVE TENDENCIES BASED ON INCIDENT CASES

The study concerns the three incidents summarized in Table 4. Ten human-related occurrences were analyzed in detail, namely:

1. (#1.2) premature test performance, i.e. failure to reduce power before test initiation;
2. (#1.4) failure to isolate leak;
3. (#1.5) first inhibition of SI;
4. (#1.6) second inhibition of SI;
5. (#2.2) continuation of pressure increase;
6. (#2.3) failure to reduce pressure;
7. (#3.2) initiation of AFWS start [subsequently: (#3.3) isolation of SGs];
8. (#3.4) failure to initiate feed and bleed cooling;
9. (#3.6) failure to detect stuck open PORV;
10. (#3.7) closure of PORV block valve.

For simplification, occurrences #3.2 and #3.3 were treated as one entity, and our analysis emphasized the clear decision-based element (#3.2) of it.

Some of the main results of the analysis are presented in Table 7. By considering only clearly known information, the occurrence-related actions are described by various *items observed*. From this *cognition-related items* were *derived* by generalizing the observed items. Of course, these generalizations are the results of our *interpretations*.

Table 7. Action-related items observed and cognition-related items derived by analyzing human-related occurrences from the three incident cases summarized in Table 4

Item of analysis	Occurrence #									
	1.2	1.4	1.5	1.6	2.2	2.3	3.2	3.4	3.6	3.7
Action-related items observed										
Commission of *unrequired action* that...			×	×	×		×			×
—(x_1) inhibits anticipated system function with detrimental consequences on equipment, availability or safety, but introduces a risk of worse consequences			×	×						
—(x_2) initiates an anticipated system function with favorable consequences, but introduces some risk for adverse progress (e.g. #3.3, or overcooling after #1.3, or failure to depressurize ('bleed') after total loss of feedwater)							×			×
—(x_3) is correct, given anticipated success of preceding (e.g. diagnosis of valve state), parallel, or subsequent (e.g. switch manipulation for startup of AFWS) performance			×	×			×			×
—(x_4) matches a current task (e.g. pressurize)					×					
—(x_5) reduces a problem due to a preceding disturbance (e.g. delay)			×	×						
—(x_6) is functionally related to preceding action					×					
Omission of *required action* that...	×	×				×		×	×	
—(x_7) would have detrimental consequences on equipment, availability or safety, but omission introduces a risk of worse consequences								×		
—(x_8) would mismatch or disturb (e.g. if the operator has to move to another part of the control room) a current task (e.g. recovery of unexpected low RCS pressure, or recovery of AFWS failure)		×				×		×	×	
—(x_9) would aggravate a problem due to a previous disturbance (e.g. delay)	×	×								
—(x_{10}) would involve a waiting period	×									
—(x_{11}) would disturb a desired progress of events, and the respective desired system state (e.g. valve closed) can be attributed to at least one item of information (e.g. signal of closure actuation)		×						×	×	
—(x_{12}) would demand to give up a plan (e.g. startup of AFWS) that is suitable to recover the direct cause of an event (e.g. AFWS pump turbine overspeed trip)								×		
—(x_{13}) should be committed after an essential success (e.g. detection of the cause of unexpected low RCS pressure)						×				

Table 7. (continued)

Item of analysis	Occurrence #									
	1.2	1.4	1.5	1.6	2.2	2.3	3.2	3.4	3.6	3.7
—(x_{14}) is likely to be unrequired in the presence of a given information (e.g. misindication of valve's position is more likely than valve's failure to close)		×						×		
—(x_{15}) is unrequired, given anticipated success of preceding, parallel (e.g. recovery of AFWS failure), or subsequent performance		×						×		
Cognition-related items derived										
Eagerness to act: (x_9/x_{10}, x_1/x_5, x_1/x_5, x_2, x_2)	×		×	×			×			×
Reluctance regarding unusual or drastic system functions: (x_1, x_1, x_7)			×	×				×		
Fixation on initial diagnosis, goal, plan or on a sequence of closely related actions: (x_9, x_9, x_5, x_5, x_4/x_6, x_8, x_8, x_8)	×	×	×	×	×	×		×	×	
Overweighting suitable (i.e. less disturbing) information: (x_8/x_{11}, x_8/x_{11}, x_8/x_{11})		×						×	×	
Root-cause orientation in corrective action selection or continuation (x_{12})								×		
Overconfidence in reliability of own performance: (x_{15}, x_3, x_3, x_3, x_{15}, x_3)		×	×	×			×	×		×
Reduced vigilance when perceiving essential success: (x_{13})						×				
Non-conservative probabilistic reasoning: (x_{14}, x_3, x_3, x_3, x_{14}, x_{14}, x_3)		×	×	×			×	×	×	×