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Review

Review of advances in human reliability analysis of errors of commission—Part 2: EOC quantification

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Abstract

In close connection with examples relevant to contemporary probabilistic safety assessment (PSA), a review of advances in human reliability analysis (HRA) of post-initiator errors of commission (EOCs), i.e. inappropriate actions under abnormal operating conditions, has been carried out. The review comprises both EOC identification (part 1) and quantification (part 2); part 2 is presented in this article. Emerging HRA methods in this field are: ATHEANA, MERMOS, the EOC HRA method developed by *Gesellschaft für Anlagen- und Reaktorsicherheit* (GRS), the MDTA method and CREAM. The essential advanced features are on the conceptual side, especially to envisage the modeling of multiple contexts for an EOC to be quantified (ATHEANA, MERMOS and MDTA), in order to explicitly address adverse conditions. There is promising progress in providing systematic guidance to better account for cognitive demands and tendencies (GRS, CREAM), and EOC recovery (MDTA). Problematic issues are associated with the implementation of multiple context modeling and the assessment of context-specific error probabilities. Approaches for task or error opportunity scaling (CREAM, GRS) and the concept of reference cases (ATHEANA outlook) provide promising orientations for achieving progress towards data-based quantification. Further development work is needed and should be carried out in close connection with large-scale applications of existing approaches.

Keywords: Human reliability analysis; Errors of commission; Human error probability; Probabilistic safety assessment

Contents

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1. Introduction

1.1. Scope and objective

A review of advances in human reliability analysis (HRA) of post-initiator errors of commission (EOCs), i.e. inappropriate operator actions under abnormal operating conditions, has been carried out. The review comprises both EOC identification on the level of human failure events (HFEs) to be integrated in a probabilistic safety assessment (PSA) model (part 1) and quantification (part 2). While part 1 has been presented in a separate article, part 2 is presented here. According to nowadays terminology [1–3], EOC quantification concerns the assessment of the probability of a HFE type defined in connection with the active role of plant operators: *failure or unavailability of a component, system or* function *that results from the performance of an action*. The review carried out in this area is intended to inform analysts and researchers aiming at a comprehensive (large-scale) quantification of EOCs in PSA studies.

1.2. Background and overview

Existing PSA guidelines do not require comprehensive EOC consideration in post-initiator HRA because of methodological problems [1,3]. The main problem associated with EOC quantification is closely related to the operator's active contribution to a HFE. To derive a plausible estimate of a human error probability (HEP) identified as contributing to a specific inappropriate action, specific causes of decision errors have to be taken explicitly into account. However, a large number of factors can affect decision making; moreover, the factors that are important for a given decision depend strongly on the context. The impact of this context is not necessarily obvious, or only part of it has an impact on human reliability [4]. Nevertheless, there are cases of EOC quantification carried out by means of HRA methods widely applied in nowadays PSA studies. These cases of so-called *first generation HRA* are very briefly reviewed in Section 2.

The problem of EOC quantification is tackled as well by undergoing developments of HRA methods of the so-called *second generation*. Historically spoken, this generation comprises advanced developments undertaken in response to directive publications on context and human reliability and reviews of respective shortcomings in HRA practice [4–6]. Speaking in more technical terms, the second generation includes features like:

- more detailed models of decision-based or cognitive errors (opposed less detailed models like *time reliability correlation* for diagnosis failure quantification applied in first generation methods); and the frequently associated
- modeling of multiple contexts of a given scenario, in order to explicitly account for conditions leading to increased HEPs in decision making.

Table 1 presents high-level characterizations of the EOC HRA capability of emerging methodological developments. A review of quantification advances published so far (ATHEANA, CREAM, GRS, MDTA and MERMOS) is presented in Section 3. Section 4 briefly discusses the contributing factors identified in various EOC quantification cases. Section 5 summarizes the state of development and gives recommendations in terms of orientations for further development work. The paper is concluded in Section 6. More details on the review are presented in a separate report [7].

2. First generation HRA

In first generation HRA practice, the quantitative assessment of a given operator task or error is emphasizing the nominal scenario context, i.e. the context corresponding to default features of the procedural guidance, training, indications and the like. For instance, the assessment of a HEP for a decision task based on display reading is usually driven by assumptions—like the availability of the required

Table 1
High-level characterization of the EOC HRA capability (post-initiator) in emerging developments of second generation methods

Method	Guidance for EOC search on the level of HFEs?	Original guidance for HFE quantification?
ATHEANA: *A Technique for Human Event Analysis* ([5,8,9]; most complete: [8])	Yes	Yes
MERMOS: *Méthode d'Evaluation de la Réalisation des Missions Opérateur pour la Sûreté* ([10–13]; most complete: [12])	No[a]	Yes
CREAM: *Cognitive Reliability and Error Analysis Method* [14]	No[b]	Yes
GRS: EOC HRA method developed by *Gesellschaft für Anlagen- und Reaktorsicherheit* [15]	Yes	Yes
MDTA: *Misdiagnosis Tree Analysis* method ([16–18]; most complete: [18])	Yes	Yes
CESA: *Commission Errors Search and Assessment* method ([19–21]; most complete: [21])	Yes	No[c]

[a]Published MERMOS descriptions emphasize the quantification of a so-called human factors mission, defined as a macro-action meant to restore or maintain a required safety function. The assessment may involve EOC quantification for a mission, in which the operator must maintain a required safety function (e.g. safety injection in the first hour after a loss of coolant). However, the published guidance does not present details on mission identification: the missions are determined from a functional analysis of the plant after an initiating event [12, p. 853], and this step is carried out by the PSA analyst, with the help of the HRA analyst if necessary [12, p. 856].

[b]CREAM presents guidance for the identification of cognitive function failures for a task assumed as known from PSA.

[c]HEPs from the handbook of the THERP (Technique for Human Error Rate Prediction [22]) method were used in the EOC pilot study [20]. An outline of a method for alternate quantification is summarized in [23]; a publication on more details is under preparation.

instrumentation, and the adequacy of the procedures and training with respect to the implication of the displayed parameters—representing the nominal conditions in the identified PSA scenario.

Table 2 lists examples of such kind of quantification. The EOC probabilities are mainly estimated by means of three first generation HRA methods, namely: *Accident Sequence Evaluation Program* (ASEP) [24], *Human Error Assessment and Reduction Technique* (HEART) [25], and *Technique for Human Error Rate Prediction* (THERP) [22]. Increased EOC probabilities are shown for cases with adverse performance conditions identified (e.g. *no EOP* for EOC 1.5) and/or with no modeling of recovery (e.g. EOC 1.4). Quantification based on THERP tends to produce rather low EOC probabilities, especially if the conditions (in particular, the procedural guidance for the indications in the scenario) are supporting successful performance and if error correction is explicitly credited (e.g. EOC 1.2). In all applications, it is uncertain whether the applied HEPs (e.g. THERP values for display reading used in the EOC 1.6 HRA) are suitable for the quantification of potential decision errors.

3. Second generation HRA

The problem with the 'single-context-based' quantification in first generation HRA is that it is particularly uncertain whether a so-obtained HEP covers adverse deviations as well (e.g. the exceptional occurrence of conflicting indications unforeseen in the procedures) from the nominal conditions. The review carried out here identified three fully elaborated second generation HRA methods directly tackling this problem: ATHEANA, MERMOS and MDTA (see Table 1 for references). These methods are presented in Sections 3.1–3.3. In addition, the GRS method [15] is presented in Section 3.4, since it addresses adverse combinations of performance conditions and cognitive factors. CREAM [14] is reviewed in Section 3.5, since it is a second generation method addressing cognitive aspects, which are relevant for decision making in situations with EOC opportunities. A brief overview of other approaches is presented in Section 3.6.

Even in a review of first generation HRA methods, it is difficult to define criteria allowing a meaningful evaluation under the consideration of both the various aspects of a method and the usual practice of non-literal applications of methods. The problem is seen as fortified when dealing with second generation HRA, since this is an area of undergoing research, especially in the field of decision error quantification. An analyst is not in a position to choose from a set of methods widely accepted (and understood) by utilities and authorities. Thus no formal criteria were explicitly applied in the review. The comments provided on the specific methods presented in Sections 3.1–3.5 are of more implicit character. They are driven by high-level aspects of practicality and reproducibility: Is it clear from the provided guidance how the method would work in PSA practice? To what extent is an external reviewer able to verify the adequacy of a HEP result? The first question concerns simple aspects like the availability of a PSA-related quantification example. The second question is supposed to identify critical features like reliance on direct numerical estimation or the non-traceable derivation of the HEP database.

Table 2
EOC quantification with first generation HRA methods

Source (study)	EOC (HFE)	Context (system, scenario)	EOC probability	Quantification details (excerpt)
German PSA, PWR (pressurized water reactor) [26]	**1.1**. Premature switchover to sump recirculation	Contribution to failure of low-pressure injection (LPI) after LOCA (loss of coolant)	10^{-2}	Screening value based on ASEP
French PSAs, 1990, EPS 900 and 1300, PWRs [27,28]	**1.2**. Termination of SI (safety injection)	Contribution to failure of early inventory makeup after LOCA	5.4×10^{-5}	HEP (based on simulator exercise data) for procedure application, combined with HEPs (mainly based on THERP) for correction options from additional indications and personnel
	1.3. Isolation of SG (steam generator) relief valve	Contribution to continuous leak through ruptured SG	2×10^{-1}	HEP from simulator exercise statistic; potential for stereotype response slip
British PSA, 1994, Sizewell B, PWR [30]	**1.4**. Termination of bleed and feed operation (pressurizer relief valve (PORV) closing or SI stop)	Scenario with loss of feedwater (FW), and manual start of feed and bleed cooling	2×10^{-2}	HEART; basic HEP of 3×10^{-3}, upward adjustment due to *unfamiliarity* and *objectives conflict*; no recovery routes modeled
Finnish PSA, 1996, Loviisa 1, PWR [29]	**1.5**. Primary circuit dilution	Situation when high capacity makeup pump has to be in operation during startup dilution and all RCPs stop	4×10^{-1}	Special model for quantifying erroneous actions after correct diagnosis; HEP of 4×10^{-1} driven by: *no EOP* (*emergency operating procedure*), and *stress*
EOC pilot study, CESA (EOC identification) and THERP (quantification), Swiss reference PSA, PWR [20]	**1.6**. Termination of SI	Contribution to failure of early inventory makeup after LOCA	6.4×10^{-5}	THERP; HEPs for procedure application under *stress*, combined with HEPs for correction options from additional indications and personnel
	1.7. FW back-throttling or stop of special and emergency FW pumps and inhibition of restart	Scenarios with degraded secondary CCW (component cooling water)	6.2×10^{-4}	As for EOC 1.6; EOC 1.7 particularly driven by: misleading indication due to adverse scenario evolution (auxiliary feedwater (AFW) fails with delay), potential for stereotype response slip
	1.8. Start of a RCP (reactor coolant pump)	Contribution to seal LOCA in scenarios with degraded primary CCW	1.2×10^{-2}	As for EOC 1.6; EOC 1.8 particularly driven by: misleading potential in EOP and conflicting goal (prevent steam bubble)
	1.9. Isolation of RCP cooling water supply (from refuelling water storage tank (RWST))	Contribution to seal LOCA in loss of AC power scenario	1.1×10^{-3}	As for EOC 1.6

3.1. Quantification in ATHEANA

3.1.1. Method summary

In ATHEANA, a base case scenario is defined to start with a search for error-forcing contexts (EFCs). It is stated that failing to search for EFC represents a gamble that HRA method's quantification tools are based on data that adequately represent an average over the full range of weak and strong contexts, and that failure to have a proper representation of the average will almost certainly lead to an underestimate of the risk [8, p. 6–13]. This position is supported by characteristics identified from incidents and accidents, namely: (1) extreme and/or unusual conditions; (2) preexisting conditions that complicate response, diagnosis, etc.; (3) misleading or wrong information; (4) information rejected or ignored; (5) multiple hardware failures; (6) transitions in progress; (7) symptoms similar to frequent and/or salient events [8, p. 5–18]. Comprehensive guidance (over about 70 pages) is provided for EFC identification. The guidance comprises the search for potential vulnerabilities in the base case scenario and physical deviations from the base case scenario as well as the identification and evaluation of complicating factors linked to performance shaping factors (PSFs). To support

Table 3
Examples of EOC quantification with the ATHEANA method

EOC (HFE); Scenario	EFC, given scenario	EFC probability	HEP, given EFC	EOC probability[a]
ATHEANA HRA examples, US PWR [8]				
2.1. Back-throttling or shutdown of secondary cooling (FW) flow; loss of MFW (main feedwater)	Overcooling concerns (10^{-1}), and failure of multiple SG-level indicators in the first 30 min (10^{-6})	10^{-7}	5×10^{-1}	5×10^{-8}
2.2. SI termination (interruption of early makeup of primary inventory); small LOCA[b]				
2.2.1. LOCA due to pipe/vessel rupture (base case)	Rupture of PZR (pressurizer) or surge line is the cause of the LOCA	10^{-1}	10^{-1}	10^{-2}
2.2.2. LOCA through stuck-open PORV (deviating case)	PORV disk separates from the stem and lodges where it does not block flow (resulting in spurious indication of *PORV closed*)	10^{-4}–10^{-3}	10^{-1}	10^{-5}–10^{-4}
2.2.3. LOCA through stuck-open PZR safety valve (deviating case)	N/A (this LOCA variant is assumed as certainly error forcing)	1	10^{-1}	10^{-1}
ATHEANA trial application, Japanese 1100 MWe class 4-loop PWR [34,35]				
2.3. Termination of AFW during forced secondary cooling operation; SGTR (steam generator tube rupture)	4-out-of-4 failure of narrow range (NR) SG water level gauge	1.67×10^{-5}	5×10^{-1}	8.35×10^{-6}
2.4. Closure of PORV during forced primary cooling; SGTR, failure of isolation of faulted SG	2-out-of-2 failure of RCS pressure gauge, or 2-out-of-2 failure of PZR water-level gauge	1.6×10^{-3}	5×10^{-1}	8×10^{-4}
2.5. Closure of PORV during feed and bleed operation; SGTR, failure of AFW	1-out-of-3 failure of NR SG water-level gauge	8.79×10^{-2}	5×10^{-1}	4.4×10^{-2}

[a]The EOC probability is calculated by multiplying the EFC probability with the conditional HEP. For simplification, the quantification of recovery is not presented in this table. Note the recovery HEPs are 4×10^{-2} for EOC 2.1 and 10^{-1} for EOCs 2.3–2.5. The EOC 2.2 HRA does not credit recovery for the prevention of failure of early inventory makeup. However, LPI alignment is considered as a recovery option for the prevention of core damage. The HEP for this option is assessed as negligible small under the condition of the EOC [8] meaning the recovery failure would be dominated by contributions from LPI hardware failures.

[b]The ATHEANA analysis of EOC 2.2 started with the base case LOCA defined for case 2.2.1. The LOCA variants in cases 2.2.2 and 2.2.3 are findings from the EFC search.

EFC identification, detailed tables on scenario characteristics and associated error mechanisms, error types and PSFs are provided. For final quantification, probabilities of EFCs are combined with the respective conditional HEPs as shown by the EOC examples summarized in Table 3. Besides direct estimations, it is recommended to refer to the data of HEART, in order to determine the conditional HEP. A list of accident cues is provided to inform the quantification of error recovery.

3.1.2. Comments

ATHEANA represents a milestone in the field of HRA method development. The concept of EFCs—which was introduced already in 1996 [5]—is essential for providing HEP estimates based on realistic causes, and provided directive input for the research on second generation HRA. ATHEANA analyses provide potentials to complete the safety insights obtained from first generation HRA. For instance, premature termination of feed and bleed operation is addressed in the HRAs of both EOC 1.4 (Table 2, HEART, EOC probability of 0.02) and EOC 2.5 (Table 3, ATHEANA, EOC probability of 0.044). The HEART HRA does not explicitly model the context with a misleading SG-level indication. However, the result of the ATHEANA HRA suggests that this EFC cannot be neglected.

Predictive EFC identification and modeling must be seen as a rather novel and challenging HRA task (cf. [4]). Thus it is 'normal' that a method review identifies issues associated with the implementation of this difficult HRA task. One issue is that the ATHEANA guidance is rather comprehensive and complicated. For instance, EFC identification for EOCs 2.1 and 2.2 in Table 3 is documented on dozens of pages. This issue may hinder the method implementation in HRA practice or may force an implementation with an inappropriate shortcut (e.g. emphasizing EFC induced by instrumentation failures). Note a recent review states as well that ATHEANA's in-depth process is likely to be used only for a few HFEs and that an updated guide (in progress) is being produced that provides a somewhat easier to follow description [31, p. 3–154].

Another, somewhat related issue is the tendency to neglect contributions from contexts other than the EFCs considered (by the analyst) as *sufficiently strong to make the likelihood of the HFEs worth concern* [8, p. 9–65]. Other contexts may contribute as well to the HFE in question. If they are neglected, the overall result is decisively relying on the completeness of EFC identification and the adequacy of the selection of the *sufficiently strong* ones. For instance, a single EFC is modeled in the ATHEANA HRA of EOC 2.1 (Table 3, *back-throttling or shutdown of secondary cooling flow in a loss of main MFW scenario*): overcooling concern in combination with multiple failures of SG level instrumentation. The retained EFC has a probability of 10^{-7}. Thus the assumption of the adequacy of the HRA would mean that the HEP is negligible in 99.99999% of the contexts of a loss of MFW scenario. This finding appears to be difficult to defend in a regulatory HRA process. Note there are well-known instances of accident precursors with operator-induced degradations of secondary cooling in cases of available SG level instrumentation; cf. the total loss of feedwater events in Trojan [32] and Davis Besse [33]. The implication is that second generation HRA should aim at a broader modeling of contexts (instead of focusing single EFCs). Of course, the examples in Table 3 are not necessarily representative for the capability of ATHEANA. The outlook in Ref. [9] suggests that the consideration of a broad range of contexts will be better highlighted in the future version of the ATHEANA guidance.

There is much need for expert judgment regarding direct probability estimations when applying ATHEANA for context-specific HEP assessment. The method developers admit that *the ATHEANA quantification method is still under development* [8, p. 6–14]. In particular, there is lack of explicit guidance for utilizing the qualitative findings for quantification. However, the method development is undergoing. In recent research, an expert elicitation approach is outlined for the development of a set of contextual anchored probabilities. The aim is to provide reference cases (covering a wide range of contexts) to support the quantification of new situations [9].

3.2. Quantification in MERMOS

3.2.1. Method summary

A MERMOS HRA assesses the probability of failure of a so-called *human factor mission*, defined as a *macro-action* meant to restore or maintain a required safety function in a post-initiator scenario. According to nowadays terminology (e.g. [2]), a subset of mission failures defined in that way would be classifiable as EOC; e.g. the failure of the mission denoted as *not switch off of the SI pumps for more than one hour*, which is defined for a LOCA through a stuck-open PORV [13]. Table 4 illustrates the concept of context modeling for this EOC-related mission. Multiple failure scenarios are considered and explicitly modeled. Each failure scenario represents a path that leads to the mission failure [12, p. 854; 13, p. 77]. The process of failure path identification is structured by the functional requirements from the point of view of *strategy*, *action* and *diagnosis*. Path development mainly works backwards. As the path endpoint, a failure scenario is identified first. Then the analyst looks for a set of so-called CICAs (*caractéristiques importantes de la conduite accidentelle*), i.e. important characteristics of emergency operation, serving to 'explain' the failure scenario. In turn, situation features are identified to 'explain' CICAs. The failure path occurs if all path elements occur. The path elements are subjects to probability assignments; values in the range from 0.01 to 1 are obtained from expert judgment of the method user [13, p. 82]. Thus the failure path probability is the product of the individual probabilities of the path elements. And the total mission failure probability (p_F) is approximately the sum of all failure path probabilities, plus a residual failure probability (p_r) in the range from 3×10^{-5} to 3×10^{-4}, which is supposed to cover failure scenarios *that cannot even be imagined*:

$$p_F \approx p_r + (p_{11} \times p_{12} \times \cdots) + (p_{21} \times p_{22} \times \cdots) + \cdots,$$

Table 4
Failure path examples in a MERMOS HRA of an EOC-related human factor mission denoted *Not switch off of the SI pumps for more than one hour,* defined for a LOCA through a stuck-open PORV [13]

	1. Elements of a diagnosis failure path	2. Elements of a strategy failure path
Situation features	1.1. The reactor operator (RO) stops accidentally the SI pumps (e.g. test error) 1.2. Wrong information on the vessel level available to the RO 1.3. The supervisor and the safety engineer (SE) have the same information as the RO	2.1. The crew thinks the water inventory is correct 2.2. Sharp increase in the pressure within the containment 2.3. SE not in the control room (CR) or follows the strategy of the crew 2.4. Supervisor follows the strategy of the crew
CICA(s)	1.4. Going through the procedure step by step	2.5. Anticipation of a further operation objective 2.6. Focus on the control of the containment
Failure scenario	1.5. The crew does not start the SI pumps after stopping them accidentally for the water inventory is seen as adequate	2.7. The crew wants to restrict the increase in the pressure and the releases within the containment, and decides to limit the flow leaking through the breach by switching off the SI pumps

where p_{ji} is the probability of the ith element of the jth failure path.

The analyst is supposed to identify as many failure paths as possible; a conservative value of the failure probability is used if it is not possible to identify failure paths [12].

3.2.2. Comments

By-and-large, a set of situation features in a MERMOS failure path can be denoted as a context with an adverse effect or as an EFC in short. Such contexts are identified on the basis of a search for functional failure modes and associated characteristics of emergency operation (CICAs). In that way, MERMOS provides advanced orientations in the implementation of multiple context modeling. The method aims at the modeling of a rather comprehensive set of failure paths and proposes a rather simple structure for their identification (*strategy*, *action*, *diagnosis*).

In addition, it is a positive feature that a residual failure probability (p_r) is modeled to account for potential shortcomings in failure path identification. Of course, this is not an essential achievement, since it is easy to postulate the existence of a residual failure probability, but it is difficult to propose a substantial value for it. In MERMOS the proposed p_r range (3×10^{-5}–3×10^{-4}) is obtained from expert judgment, which in turn is based on values used in the former EdF HRA method. Nevertheless, the range seems to be reasonable in view of other suggestions of lower bound cut-off HEPs, e.g. 10^{-5} by Gertman et al. [36, p. 61], or 10^{-5}–10^{-4} by Kirwan [37, p. 204].

The most obvious issues associated with MERMOS are the lack of published information on the application in HRA practice, and the lack of published guidance for the identification of functional failure modes, CICAs and the situation features. The review (carried out here) of the MERMOS publications could not identify a fully documented HRA example. Some HRA fragments are presented, but even these fragments are incompletely documented. The failure paths in Table 4, for instance, are insufficiently explained in Ref. [13] from which they were taken.

In MERMOS, most of the path elements are directly quantified with expert judgment. It is stated that the level of path breakdown eases this judgment [13, p. 82]. As it can be seen in Table 4 however, most of the path elements are influenced by decision-based behavior of the operating crew and the supporting staff. In view of the inherent difficulties in predicting decision behavior, the extensive use of direct probability estimates must be seen as both a source of uncertainty and an issue questioning the reproducibility of the quantification results. For instance, the quantification of path element 1.1 or 2.1 may deserve a separate HRA, in order to identify the contributing factors.

3.3. Quantification in the MDTA method

3.3.1. Method summary

In the MDTA method, the EOC quantification guidance is closely connected with the steps related to EOC identification. Three elements are addressed by quantification: (a) diagnosis failure; (b) unsafe action (UA, i.e. EOC or EOO), given diagnosis failure and (c) non-recovery, given UA.

Table 5 presents an example about their quantification. Fig. 1 illustrates the integration of the EOC quantification results into an event tree developed for scenarios initiated by a small loss of coolant (SLOCA). Misdiagnosis and failure to maintain high-pressure safety injection (HPSI) are modeled as separate top events. For instance, a probability of 6.44×10^{-3} (estimated from two failure paths of the misdiagnosis tree shown in [18]) is assigned to the diagnosis of an excessive steam demand event (ESDE) in a SLOCA scenario. A probability of 0.02 for the failure to maintain HPSI is estimated under this condition. In this estimation, the UA is modeled as certain meaning the product of the two post-UA recovery HEPs yields 0.02. Table 6 presents the dominant path contributing to the ESDE diagnosis probability of 6.44×10^{-3}.

Misdiagnosis quantification is structured by three contributors (PD, OE, IF) to adverse operator responses at a decision point in the emergency operating procedure (EOP):

- In order to identify and quantify adverse decisions due to *plant dynamics* (PD), IE subgroups are examined on the basis of results of thermo-hydraulic analyses. The behavior of the plant parameters relevant for the critical decision points in the EOP is assessed for these

Table 5
MDTA method results of the quantification of premature HPSI termination identified as an unsafe action (UA) in a SLOCA scenario [18]

Misdiagnosis	Misdiagnosis probability	Probability of UA, given misdiagnosis	Probability of non-recovery		Total (product)
			Procedural guidance on recovery	STA's independent checking of CSF	
General transient event (GTRN)	3.0×10^{-5}	1	2.0×10^{-1}	1.0×10^{-1}	6.0×10^{-7}
Excessive steam demand event (ESDE)	6.44×10^{-3} (*dominant path in* Table 6)	1	2.0×10^{-1}	1.0×10^{-1}	1.29×10^{-4}

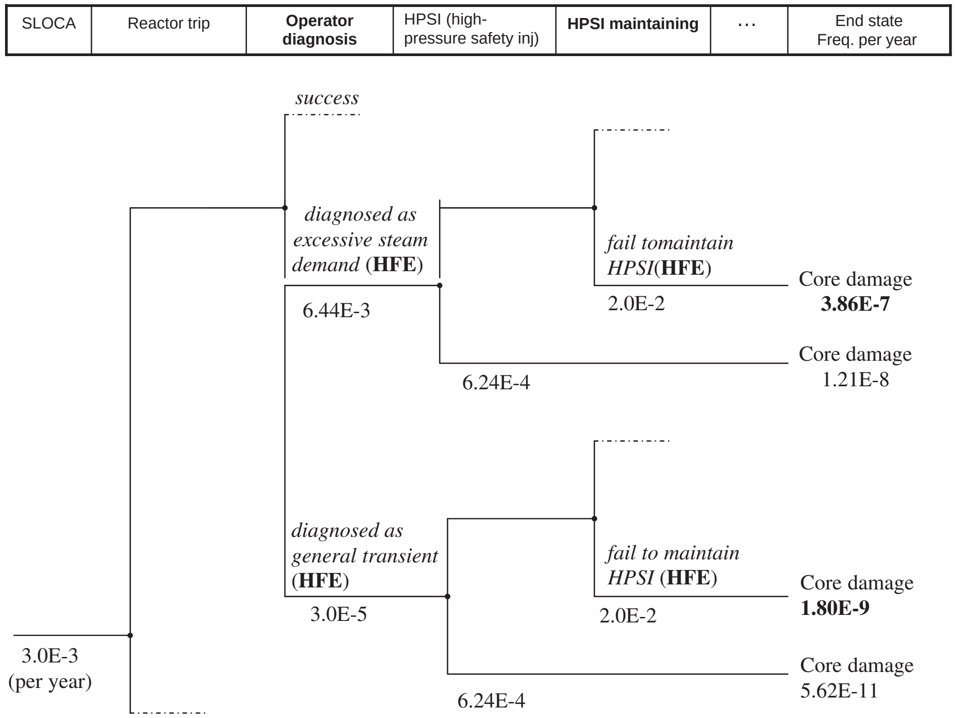

Fig. 1. Excerpts from a SLOCA event tree with EOC HFEs integrated [18].

Table 6
MDTA quantification of a path leading to an erroneous diagnosis of ESDE in a SLOCA scenario [18]

Failure contribution	Type	Probability	Quantification details
RCS SCM adequate (<15 °C)	PD	0.667	Fraction of SLOCA cases with leak sizes from 0.38 to 1.5 in out of all SLOCA cases (leak sizes from 0.38 to 1.91 in)
Decreasing trend of SG pressures	PD	1	Certain condition in SLOCA cases with HPSI operating
Misinterpretation of EOP decision rule referring to containment pressure	OE	0.006	Table 7, case "NOT & (AND or OR)". Error correction by STA not credited because CSF procedure does not cover containment pressure checking
Overall		0.004	

subgroups, and it is determined which fraction of them would force a decision contributing to misdiagnosis. In the misdiagnosis path presented in Table 6 for instance (SLOCA IE), the EOP analysis identified conditions with *adequate sub-cooling margin (SCM)* as contributors to misdiagnosis. The probability of such conditions is calculated as the fraction of SLOCA IEs, in which the SCM is indicated as adequate (i.e. IE subgroups with leak sizes from 0.38 to 1.5 in).

- Table 7 is proposed for the quantification of an *operator error* (OE) in information gathering or rule interpretation. The basic HEPs, which are in the range from 1.6×10^{-2} to 3×10^{-4}, were derived from both expert judgment and the *Caused-Based Decision Tree* (CBDT) method [38]. A HEP of 0.5 is recommended to credit error correction on the basis of a check of the critical safety functions (CSF) carried out by the shift technical advisor (STA). For instance, the logic of the decision rule related to containment pressure involves the words 'NOT' and 'AND' (see [18]), and thus a basic HEP of 0.006 (Table 7) is used to quantify misinterpretation in the path presented in Table 6. Error correction is not credited, since the STA's checking does not address containment pressure.
- A contribution from an *instrumentation failure* (IF) is quantified on the basis of the respective reliability and test interval data. For instance, the rate (3.3E-7/h) for *pressure transmitter drifts high* is applied to quantify the failure of containment pressure indication. The test interval is 18 months. A β factor of 0.1 is used to quantify multiple channel failures, yielding the

Table 7
Basic HEPs for OE quantification in the MDTA method [18]

Cognitive function	Detailed items	Basic HEP
Information gathering	Existence of other confusing information similar to the required information	1.0E-2
	Information on more than one object is required	1.0E-2
Rule interpretation	The logic of the decision rule	
	• AND or OR	3.0E-4
	• NOT	2.0E-3
	• NOT & (AND or OR)	6.0E-3
	• AND & OR	1.0E-2
	• NOT & AND & OR	1.6E-2

failure probability of 0.0002 assigned to the respective IF limb [18].

For scenarios with at least 30 min available for post-UA recovery, the method proposes the consideration of two recovery paths (options), namely (1) procedural guidance on the recovery (HEP of 0.2), and (2) independent checking (by the STA) of the status of the critical safety functions (HEP of 0.1 if more than 1 h available; 0.2 otherwise); i.e. the total recovery HEP can be 0.02 ($= 0.2 \times 0.1$) in the best case. Table 8 summarizes these recovery HEPs, which are adapted from the CBDT method.

3.3.2. Comments

The MDTA quantification approach is a step forward in making EOC HRA feasible. It provides useful input to start a fruitful debate on details of the implementation of advanced human error quantification. Issues of such a debate are outlined next.

The MDTA method addresses only two types of EFCs, i.e. (adverse) PD and IF. Both types are considered here as very relevant. Note that adverse plant dynamics (delayed failure of AFW) have been identified as well in the first pilot application of the CESA method [20]. The short list of EFC types has the advantage that it bounds the additional effort required by an EOC HRA. Of course, one may challenge the comprehensiveness of this short list by referring to additional EFC types like the ones tabled in the ATHEANA report; e.g. *dilemmas* [8, p. 9–78]. However, the associated shortcoming is diminished since the MDTA method additionally accounts for an error in information gathering or rule interpretation.

A critical issue is associated with the HEPs proposed for OE quantification. The method description states that they were derived from expert judgment and the CBDT method. Publications on CBDT suggest that the HEPs proposed for interpretation tasks are based on THERP; yet the actual process of derivation of the probabilities is proprietary and not available for evaluation; cf. the CBDT summary in [39]. Thus the MDTA quantification can be denoted as

Table 8
Recovery quantification in the MDTA method [18]

Recovery path (RP)	Available time	Probability of non-recovery
RP1: the procedural guidance on the recovery	>30 min	0.2
RP2: the independent checking of the status of the CSF	30 min to 1 h	0.2
	>1 h	0.1

THERP-based (or judgment-based) with the contributions from two EFC types (PD, IF) on top of it. In the HRA example (Table 5), the ESDE diagnosis probability would drop from 6.44E-3 to 2.68E-4 if OE contributors are neglected. In summary, the MDTA method relies on the adequacy of THERP values (or expert judgment) for the quantitative prediction of human decision making.

Another MDTA issue refers to the treatment of dependency in a misdiagnosis path:

- Note the Swiss EOC pilot study applied THERP for the quantification of dependence between operator errors involved in an EOC path (see [20]).
- In the MDTA method, this kind of dependency issue is not addressed; cf. [18]: the operator errors in interpreting the rules related to pressurizer (PZR) pressure and level are treated as independent.

The dependency issue may require clarification in the MDTA guidance, to prevent optimistic results in misdiagnosis path quantification.

It is a positive feature that MDTA addresses the quantification of post-EOC (or post-UA) recovery by means of traceable factors, namely: time available for recovery and procedural guidance on recovery. Note the THERP adaptation in the Swiss EOC pilot study [20] applies the (by-and-large) same set of factors. There are differences in applying these factors.

The MDTA method applies the procedural guidance on CSF monitoring as a separate recovery factor. In the Swiss EOC pilot study, the CSF guidance was included in the overall evaluation of recovery: a reduced recovery HEP was used, given guidance on recovery (1) in a procedure supposed to be in use after the EOC or (2) in the separate procedure on CSF monitoring; but no additional reduction is applied in cases of (1) and (2). Thus the pilot study is more conservative in this respect.

On the other hand, the pilot study is less conservative than MDTA regarding the following features.

- In the pilot study [20], recovery is credited even if there is no procedural guidance on recovery at all. It is argued that alarms or indications induced by the EOC may provide feedback to alert the operators. Of course, the analyst has to document the cueing of recovery.

Table 9
Excerpts from the assessment guidance on cognitive factors in the GRS EOC HRA method (translated from [15])

Group	Factor example	Condition for factor triggering	Impact on task performance
A. 6 factors on goal formation	The operator may overestimate the success chance of actions considered by him	(a) Success chance greater than ~0.2	(a) Non-consideration of possibility of action failure (e.g. operator's planning does not account for error detection and correction).
B. 7 factors on learning and experience	The operator may be slower in recalling knowledge in coping with unfamiliar problems and faster in recalling knowledge in coping with familiar problems. In extreme cases, recalling may fail totally	(a) The knowledge on familiar problems is strongly stored in memory due to training and practice (b) Stressors like time pressure may impede access to less familiar knowledge	(a) Diagnoses or actions may be delayed or missed. (b) The operator may refer to familiar strategies; e.g. using indications or signals normally used.
C. 5 factors on coping with stressors	The search for ad-hoc solution on single aspects may be made instead of taking actions based on accurate planning	(a) An evitable requirement to cope with a situation which involves the risk of a failure with severe consequences	(a) Required actions may be delayed or missed. Ad-hoc solution chosen may result in additional failures or damages
D. 5 factors on connecting information to a consistent picture of the performance situation	The operator may neglect (or underweight) information which is displayed as unchanged for a longer time and thus has a reduced value of novelty	(a) Information displayed as unchanged for a longer time (as described in the factor definition). (b) Given lack of time, the operator may further increase his focus of attention on aspects, which are alternating, new or obvious	(a) The operator may consider such information as less important and thus may neglect it in the process of diagnosis and action selection (b) The factor may fortify the effect of other factors (in groups B and C)
E. 1 factor on capacity limits	The amount of information to be processed may exceed the limits of conscious cognitive processing	(a) Information overflow (multiple alarms) after an abnormal event (b) Efficient connecting and structuring of information may counteract with this limitation	(a) Work-overload may lead to non-consideration of a certain piece of information

- Moreover, the pilot study credits as well recovery in case of time window (TW) below 0.5 h. Note the MDTA guidance suggests a TW > 0.5 h criterion for the inclusion recovery. Operational events indicate however a notable portion of EOCs recovered within 30 min [40].

In summary, the treatment of recovery in the Swiss EOC pilot study might be too conservative for cases with more than 30 min available and diverse procedural support (procedure in use after the UA, and separate procedure on CSF monitoring supposed to be in use throughout the scenario). Evaluations of recovery contexts in operational events may support lower HEPs.

3.4. *Quantification in the GRS method*

3.4.1. *Method summary*

To quantify a potential EOC identified, the GRS method [15] addresses cognitive factors and ergonomic factors interacting with human cognition. Table 9 presents an overview of the cognitive factors and the summarized version of the provided assessment guidance. The compilation of ergonomic factors—structured by the headings of *information* (e.g. readability of indications or accessibility of procedure) and *action* (e.g. sequential arrangement of steps or accessibility of equipment)—is similar to other, well-known compilations (e.g. [22]). Based on the assessment of these cognitive and ergonomic factors, the method user is supposed to determine a performance load level (*Beanspruchungsstufe* in German) according to the guidance provided in Table 10. The assignments of HEPs to the levels are based on expert judgment of the method developers; the HEP of 0.01 is justified with ASEP estimates and HRA review results. The HEPs in Table 10 are meant to be used in a screening analysis. Detailed quantification using an expert elicitation process is recommended, given that an EOC quantified with a screening probability shows an essential contribution to the PSA result. A process with shift and training personnel involved is recommended: the judgment is decomposed

Table 10
EOC probabilities (mean values for screening) proposed in the GRS method for five performance load levels (compiled and translated from [15, Ch. 8])

Performance load level	Description	HEP
1	None of the evaluated performance conditions has the potential for an adverse impact on decision making	0
2	Essential performance conditions are advantageous. Recovery is possible	0.01
3	Essential performance conditions are partially adverse. Recovery is possible	0.1
4	Essential performance conditions are mainly adverse. Recovery is possible	0.5
5	Essential performance conditions are mainly adverse. Recovery is *not* possible	1

into stages, and the experts are asked to choose HEP intervals [15, p. 179].

3.4.2. Comments

It is an advanced development that the GRS method provides comprehensive and systematic guidance on cognitive aspects of EOC opportunities; the guidance provides a useful basis for the elaboration of an EFC identification procedure. As it can be seen in Table 9, the cognitive factors are mainly formulated as tendencies of human behavior. Thus the assessment guidance is close to the guidance on *cognitive tendencies* developed by Mosner-on-Dupin et al. [6].

An issue related with the GRS guidance is the lack of illustration. No PSA-related example is presented. Only one example related to operating experience (the TMI accident, 1979)—which is more relevant to the history than to the current state of nuclear power plant (NPP) operation—is outlined. Moreover, this example lacks compliance with the presented method guidance. It is not shown how a systematic method application, i.e. by going through the list (Table 9) factor-by-factor, would work. Some of the factors are formulated in a rather 'soft' manner meaning they appear as applicable to a large number of post-initiator situations.

HRA trial applications may provide insights on the usability of GRS guidance. It is rather easy to identify adverse cognitive factors in hindsight for an operational event with a severe EOC involved. Predictive HRA applications are much more difficult: while the addressed PSA scenario provides a low level of specification of the variety of conditions affecting human performance, the estimated HEP is supposed to account for these conditions [41].

It is a positive feature of the GRS method that the assessment of the performance load level is in the focus of expert judgment of the method user meaning there is no need for direct probability estimation. A simple scale of five discrete HEP values is seen here as reasonable for HRA purposes. More generally spoken, such kind of scale is a useful element of the 'bridge' (cf. [42]) between qualitative findings and quantitative predictions. However, the provided level descriptions in the GRS scale are rather generic, and there is no explicit guidance on how to choose a level on the basis of the findings of the assessment of cognitive and ergonomic factors. Thus the reproducibility of the results would be an issue in cases of applications in HRA practice.

Another positive feature of the GRS method is the use of screening values for determining those EOCs that deserve more detailed quantification. In view of the effort required to obtain a substantially supported EOC probability, this kind of prioritization would be helpful for HRA in PSA practice. However, the process (expert elicitation involving direct estimations of HEPs) proposed for detailed quantification may restrict the applicability of the method. Due to resource limitations for instance, a method user may not be able to organize an expert elicitation process.

3.5. Quantification in CREAM

3.5.1. Method summary

In a basic CREAM analysis, the assessment of a generic action failure probability—defined as the probability of performing an action incorrectly for a task as a whole—is mainly based on the evaluation of a pre-defined set of common performance conditions (CPCs), e.g. *availability of procedures/plans*. The evaluation results determine a point on a discrete scale of four control modes. Failure probability (p) intervals are assigned to these modes: e.g. $0.1<p<1$ to the 'worst' control mode labeled *scrambled*, and $5\times10^{-6}<p<10^{-2}$ to the 'best' mode labeled *strategic*. The basis for these intervals is described as *commonly accepted estimates in the available HRA literature* [14, p. 241].

The purpose of an extended CREAM analysis is to produce a set of specific action failure probabilities. The highest probability in this set is proposed to be used as the final task failure probability. For this purpose, the task is decomposed into actions (also denoted as *task steps or activities*), and the likely (predominant) cognitive failure type has to be determined for each action of the task in question. A list of 13 failure types—structured by four cognitive functions (observation, interpretation, planning and execution)—is provided together with basic values of the associated failure probabilities, which are in the range from 5×10^{-4} for the execution failure type denoted as *action on wrong object* through 0.2 for the interpretation failure type denoted as *faulty diagnosis*. It is stated that these basic values have been taken from a variety of sources (e.g. [22,43,44]). A basic value is subject to adjustment by a factor, which in turn depends on the results of the assessment of the common performance conditions. Theoretically, a total adjustment factor (i.e. the product of the CPC-specific factors) in the range from 0.05 to 4000 is possible. Expert judgment and a review of HRA techniques (especially HEART) provided the basis for the numerical values of the CPC-specific factors [14, p. 234–54].

3.5.2. Comments

CREAM represents progress in ranking error opportunities and in accounting for cognitive failure modes. It is debatable whether CREAM is directly applicable for the quantification of an EOC HFE (*basic event that represents a failure or unavailability of a component, system or* function *that is caused by an inappropriate action*) in the sense of the terminology used in contemporary PSA [1,2].

Although CREAM does not make use of the EOO/EOC distinction, a problem is that the method tends to focus on omissions (omission of correct decisions as well as of actions). It appears that the main effect of a failed cognitive function is also treated as omission. The failure consequences are not analyzed. This may be problematic for failure modes with different consequences, e.g. *wrong object observed* (an EOC) vs. *observation not made* (an EOO); the *wrong object* may trigger an action worse than the EOO.

CREAM does not present a model of multiple contexts, i.e. CPC evaluations and failure probability assignments are supposed to reflect the nominal (or base) case of a scenario. A respective extension of explorative nature is outlined in a recent approach for the probabilistic modeling of control modes [45]. In this approach, the possibility of multiple contexts can be modeled as a probability distribution for the CPC levels (e.g. probability of 0.7 for day time, and 0.3 for night time).

A positive feature of CREAM is the proposed scale of control modes correlating with failure probabilities. As already presented in the GRS method evaluation, such kind of scale is a useful element of the 'bridge' between qualitative findings and quantitative predictions. CREAM's scale of control modes is more user-friendly than the GRS scale of performance load levels, since CREAM provides explicit guidance for the choice of a control mode under a given set of performance conditions.

CREAM is a promising approach for its efforts in the identification of cognitive failure types relevant for EOC quantification. However, the treatment of cognitive failures has the limitation that CREAM quantifies a unique, most likely error mechanism per subtask, systematically neglecting the contribution of the other mechanisms.

Concerning the derivation of the CREAM database for failure probabilities and adjustment factors, data from first generation HRA methods (e.g. THERP and HEART) were used. Of course, a CREAM HRA result thus relies in part on the adequacy of HEPs from first generation HRA methods. The failure probability and adjustment factor derivation process itself is however not explicitly outlined meaning reproducibility is a critical issue of the CREAM database. This shortcoming may lead to user problems. For instance, CREAM proposes a basic value of 0.2 for the probability of a *faulty diagnosis* [14, p. 252]. In order to apply this high value in a context-specific manner, some information on the underlying performance conditions would be very useful for a CREAM user. The value (0.2) would remain unmodified, given the CPC levels shown in Table 11 meaning 0.2 would return as the final result. With the same set of CPC levels however, the final result would be 0.01, given that a *decision error* is selected as the predominant type of a cognitive failure. Thus it deserves explanation why a *faulty diagnosis* is 20 times more likely than a *decision error*. The implication is that a CREAM analysis is sensitive to the selection of the predominant type of a cognitive failure.

It is a positive feature that the failure probability values proposed by CREAM are classified as first approximations, with the aim of demonstrating the principles of the method [14, p. 252]. It is not however clear what are the directions to follow in order to increase the quality of the proposed data. Also, for some cognitive functions such as planning, it is difficult to set up credible experiments for enhancing data collection.

3.6. Other approaches

Finally, it is worth mentioning that various approaches exist to better utilize empirical data for the derivation of context-specific HEPs (e.g. [46–49]). These approaches are in an exploratory phase, exclude EOCs from the scope, or do not provide explicit HRA guidance in the publications available so far. For instance, the outlined guidance of the *Nuclear Action Reliability Assessment* (NARA) method

Table 11
Levels of common performance conditions (CPCs) resulting in no modification of the basic HEP for an interpretation failure in an extended CREAM analysis [14, p. 255]

CPC	Level	Expected effect on performance reliability
Adequacy of organization	Efficient	Improved
Working conditions	Compatible	Not significant
Adequacy of MMI (man–machine interface) and operational support	Supportive	Improved
Availability of procedures/plans	Appropriate	Improved
Number of simultaneous goals	Fewer than capacity	Not significant
Available time	Temporarily inadequate	Not significant
Time of day	Day-time (adjusted)	Not significant
Adequacy of training and preparation	Adequate, low experience	Not significant
Crew collaboration quality	Efficient	Not significant

Possible basic HEPs for interpretation failures are: 0.2 for *faulty diagnosis*; 0.01 for *decision error*; 0.01 for *delayed interpretation* [14, p. 252].

does not address EOCs; it is announced that a prototypical approach to EOC quantification has been developed [46].

The underlying objective of data-based HRA however must be seen as positive development, since reliance on direct HEP estimation is a strong argument calling in question the value of HRA for the derivation of safety insights. Note data support was an explicit criterion that drove the process of the development of the NARA method [46].

4. Qualitative quantification results: contributing factors

All the quantification cases referred to in Sections 2 and 3 (except the screening value assignment for EOC 1.1 in Table 2) were qualitatively evaluated. Table 12 presents the factors identified as contributing to the elicited HEPs. Factors assessed here as relevant for specific causes of decision errors are presented as a special group. *Stress* and *unfamiliarity* are assigned to this group, since they can impact the reliability of verification of the adequacy of a considered action; e.g. stress induced by time pressure may force that the verification is not carried out.

Debatable issues associated with some of the assignments of factors to EOCs are:

- The contribution from an operator error (OE) in rule interpretation, quantified in the MTDA HRA, was classified as a random error. One may reclassify this contribution as *complexity of a decision rule in the EOP*. However, the rule logic appears to be *normal* for contemporary EOPs (see Table 6)—as suggested as well by the rather low HEP of 0.006 applied to it.
- A contribution from *random errors* was as well assigned to the MERMOS case although this is not explicitly indicated in Table 4. As presented in the method summary (Section 3.2), the contribution from a residual failure is quantified in each MERMOS HRA. By-and-large, this contribution is assessed here as classifiable under the heading of *random error*.
- The reviewer did not fully understand the CICA of the diagnosis failure path presented in Table 4 (MERMOS HRA). Therefore, no factor was assigned to it.

The assignments show that two or more factors are contributing to most of the quantification results; e.g. *conflicting goals* and *misleading procedure* are identified as contributing to the start of an RCP under inappropriate operating conditions (Table 2, EOC 1.8). In the majority of cases, *random errors* and *stress* are driving the HEPs obtained from first generation HRA, which is typical for the THERP HRAs used. As outlined in Ref. [20], adaptations (based on expert judgment) of THERP were required for quantifying other, more specific factors like *conflicting goals*.

Instrumentation failures contribute to most of the EOCs quantified in second generation HRA (ATHEANA and MDTA). Factors common to both (first and second generation HRA) are: misleading indication due to adverse

Table 12
Contributing factors identified from various cases of EOC quantification

Contributing factor	Case (method)	
	First generation methods	Second generation methods
Factors relevant for specific causes of decision errors		
Conflicting goals or anticipation of further operation objective	Table 2, EOC 1.4 (HEART) Table 2, EOC 1.8 (THERP)	Table 3, EOC 2.1 (ATHEANA) Table 4 (MERMOS)
Misleading indication due to adverse scenario evolution or IE variant	Table 2, EOC 1.7 (THERP)	Table 3, EOC 2.2 (ATHEANA) Table 5 (MDTA)
Misleading indication due to instrumentation failure	–	Table 3, EOC 2.1 (ATHEANA) Table 3, EOC 2.2 (ATHEANA)[a] Table 3, EOCs 2.3–2.4 (ATHEANA) Table 5 (MDTA)[b]
Procedure unavailable or misleading	Table 2, EOC 1.5 (misc.) Table 2, EOC 1.7 (THERP)	Table 5 (MDTA)[c]
Stress	Table 2, EOC 1.5 (misc.) Table 2, EOCs 1.6–1.9 (THERP)	–
Unfamiliarity	Table 2, EOC 1.4 (HEART)	–
Miscellaneous (misc.) factors		
Potential for a stereotype response slip	Table 2, EOC 1.7 (THERP) Table 2, EOC 1.3 (misc.)	–
Random error in procedure application (rule interpretation, information gathering, display reading)	Table 2, EOC 1.2 (misc.) Table 2, EOCs 1.6-1.9 (THERP)	Table 4 (MERMOS) Table 5 (MDTA)

[a]The instrumentation failure (IF) contribution to EOC 2.2 is small; see subcase 2.2.2 in Table 3.
[b]The IF contribution to this EOC (HPSI termination) is very small; see Fig. 4 in [18].
[c]CSF procedure does not cover containment pressure checking (see Table 6).

scenario evolution or IE variants (e.g. addressed in MDTA under the heading of *plant dynamics*), conflicting goals and random errors.

5. Summary and recommendations

5.1. Shortcomings in decision error quantification

Methods mostly applied so far for quantifying selected EOCs in first generation HRA are THERP and HEART. Essential shortcomings of such quantification are:

- The quantification is based on a single context (i.e. the nominal one) and thus it is uncertain whether the HEP obtained covers as well the full range of contexts (especially the EFCs) for the HFE in question.
- It is uncertain whether the used HEPs are applicable to errors in decision making.

Emerging methods of second generation tackling these problems are: ATHEANA, MERMOS, CREAM, GRS and MDTA. Table 13 provides a high-level summary of their features. The quantification of multiple contexts is explicitly guided in ATHEANA, MERMOS and MDTA. However, an increased effort (especially when going through the ATHEANA guidance step-by-step) would be required for the identification of contexts with increased failure probabilities. Of course, the problem of incompleteness is inherently associated with any result of such a search. A respective shortcoming of ATHEANA is that the presented guidance and HRA examples tend to suggest that this problem is negligible.

Applications available so far (Table 12) indicate promising trends in explicitly addressing decision-related factors like *misleading indications* (ATHEANA and MDTA) or *conflicting goals* (ATHEANA and MERMOS).

PSA-relevant experience with second generation methods is rather limited (ATHEANA, CREAM, GRS and MDTA), or respective information is published on a poor level of detail (MERMOS). For some methods, it is even not totally clear how they would work in PSA practice: a relevant is example is not provided at all (GRS), or the example provided does not cover an EOC HFE (CREAM) or is inadequately documented (MERMOS).

All the methods have weaknesses with respect to the assignment of context-specific HEPs.

- There is strong reliance on direct numerical estimation of an HEP (ATHEANA and MERMOS), or the assignment rules are rather vague (GRS).
- It is not documented in detail how the HEPs proposed in the method database were derived (CREAM, GRS and MDTA).
- In some methods (CREAM, MDTA), the derivation of HEPs for decision error is based on HEPs proposed in first generation methods like THERP. As indicated above however, it is uncertain whether the HEPs proposed in methods like THERP are applicable for this purpose.

EOC quantification with existing methods is therefore likely to induce problems regarding practicality and reproducibility. Moreover, it is particular uncertain

Table 13
HFE quantification in second generation HRA methods

Method	Subject of quantification	Example provided relevant to contemporary PSA?	Essential basis of context-specific HEPs
ATHEANA	Multiple contexts; emphasis on EFCs	Yes: [8,34]	• Expert judgment of the method user
MERMOS	Multiple contexts; emphasis on failure paths associated with so-called CICAs	Yes: [13]; but very concise example; no discussion of probability assignments	• Expert judgment of the method user
CREAM	Nominal context	Yes: [14, Ch. 9]; but no EOC HFE case	• Expert judgment of the method developer; basis: review of the HRA literature (THERP, HEART, etc.)
GRS	Single context as defined for the HFE identified	No: the EOC (SI termination) in the TMI-2 event (1979) is presented as an example	• For screening: expert judgment of the method developer; basis: ASEP and HRA review results • For HFEs retained after screening: expert judgments of the method user and plant experts
MDTA	Multiple contexts; limited to three types (PD, OE, IF); cf. Section 3.3	Yes: [16] (qualitative), [18] (qualitative and quantitative)	• For strong EFCs (PD, IF): HEP = 1 (expert judgment) • Else (OE): Expert judgment of the method developer; basis: CBDT method (which in turn utilizes THERP values)

whether aspects related to human decision making are adequately represented in the final HEP obtained.

5.2. Orientations for further development work

To overcome the EOC quantification problem, it is not recommended to start development work from the scratch. Instead, it is deemed worthwhile to take into account the achievements available so far in second generation HRA. The existing methods and approaches presented in Section 3 have (or point to) advanced features, which in turn provide orientations for further development work. These advanced features are briefly outlined below.

Ideally, a quantification method should combine all of these features. Since such a method does not exist, the list gives orientations for development work and adaptation requirements. An analyst intending to quantify EOCs on the basis of existing methods may select any method in the sense of an approach: adaptation may be applied to account for as many desirable features as possible; and shortcomings in this respect may be clearly highlighted as a limitation of the provided EOC quantification.

(a) *Modeling multiple contexts of a scenario based on detailed EFC identification:* As one of the key concepts of the ATHEANA method, this feature is as well an element of the methods MERMOS and MTDA. The feature is viewed here as essential, since decision behavior is very sensitive to the context, i.e. small changes in the context can have important impacts, which are likely to remain unconsidered in a quantification based on nominal conditions (cf. the introductory notes in Section 3).
(b) *Accounting for shortcomings in context identification and evaluation:* This feature is an element of the methods MERMOS and MDTA. As commented in Section 3.1, a problem with the ATHEANA guidance is that it tends to base the quantification on a small set of EFCs identified as essential. Thus the adequacy of the result strongly relies on the analyst's ability to identify essential EFCs. This problem is diminished in the methods MERMOS and MDTA. For instance, MERMOS guides to explicitly quantify a number of failure paths—initiated by adverse situation features (which act as EFCs)—and even proposes to use a residual failure probability to cover unforeseen situation features.
(c) *Providing concise and effective guidance for the identification of adverse contexts:* As commented in Section 3.1, a problem with the ATHEANA guidance for EFC identification is that it is rather sophisticated. The development of a rather simple framework—like in MERMOS (process of failure path search structured under three headings: *strategy, action and diagnosis*) or MDTA (*plant dynamics, instrumentation failure and operator error*)—appears to be a promising concept to overcome this problem.
(d) *Providing reference (or anchor) cases to support context-specific EOC probability assessment and thus to avoid the analyst's need to make direct probability judgment:* This feature is element of the ATHEANA outlook [9] and the recent outline of an EOC quantification method [23,49]. It is a promising approach to overcome the recent dilemma in decision error quantification. Reliance on direct probability judgment leads to reproducibility problems in methods (e.g. MERMOS) rejecting to use HEP values from first generation methods like THERP. On the other hand, the use of such HEP values is associated with essential uncertainty about the coverage of decision-based error modes.
(e) *Addressing cognitive demands and tendencies:* This feature is element of the GRS method and CREAM. For instance, the GRS method explicitly separates *cognitive factors* (associated with emphasis of second generation HRA) from *ergonomic factors* (associated with emphasis of first generation HRA), and presents a structured guidance in accounting for them (see Table 9).
(f) *Applying a simple discrete scale on the correlation between qualitative findings and error probabilities:* This feature is element of the GRS method and CREAM. Two stages may be distinguished: (1) qualitative findings are linked to some ranking index (GRS: *performance load level*) or ranking category (CREAM: *control mode*), i.e. some kind of interval scale is defined in that way, and (2) this interval scale is calibrated by assigning HEPs to the indices or categories. Although stage (2) is based on expert judgment, stage (1) is a valuable interim result usable for data-based derivation of context-specific HEP values (cf. [42]).
(g) *Using screening values for initial quantification:* This feature is element of the GRS method and CREAM. It is viewed here desirable because of the effort required for the implementation of feature (a). Such effort can be avoided for those EOCs for which the initial quantification concludes a negligible or acceptable contribution to the overall risk.
(h) *Aiming at data-based EOC probabilities by means of advanced event analysis techniques:* This feature, which is element of some of the 'other approaches' (e.g. NARA) outlined in Section 3.6, is associated with future data analysis required to increase the credibility of quantitative EOC prediction and thus the acceptance of EOC HRAs.
(i) *Accounting for EOC recovery by means of traceable factors:* This feature is element of the MDTA method. HRA should adequately account for recovery potentials, in order to obtain a realistic estimate of the risk contributions from human errors. The use of traceable factors is a desirable element of a formalized process of recovery quantification.

6. Conclusions

The review of advances in the quantitative HRA of errors of commission (EOCs) addressed both EOC cases quantified with first generation methods (e.g. THERP) and cases quantified with second generation methods (e.g. ATHEANA). In the context of the latter, an in-depth review of five second generation methods was carried out (ATHEANA, CREAM, GRS, MERMOS and MDTA). The essential advanced features of second generation HRA are on the conceptual side, namely to envisage the modeling of multiple contexts for an HFE to be quantified (ATHEANA, MERMOS and MDTA), in order to explicitly address adverse conditions (*EFCs* in ATHEANA; CICA-related *situation features* in MERMOS) leading to increased HEPs. Moreover, there is promising progress in providing systematic guidance to better account for cognitive demands like interpretation requirements (CREAM) and cognitive tendencies like success chance overestimations (GRS) and EOC recovery by means of traceable factors (MDTA). Problematic issues are associated with the implementation of multiple context modeling (EFC search effort, reproducibility and completeness) and the assessment of the context-specific HEPs (reliance on expert judgment or data from first generation methods like THERP). Approaches for task or error opportunity scaling (CREAM and GRS) and the concept of reference cases of context-specific HEPs (ATHEANA outlook) provide promising orientations for achieving progress towards data-based EOC quantification.

HRA research on EOCs is undergoing since more than 10 years (e.g. [5]). Although much research on method development has been carried out, nowadays analysts are not in a position to choose from a set of working EOC HRA methods, i.e. methods applicable under the constraints in industrial PSAs and addressable in a regulatory review process. Much method development work with conceptual emphases has been carried out so far. On the other hand, experience with large-scale applications is rather limited. To establish a set of working methods, it is recommended to carry out further development work in close connection with the outstanding tasks outlined in Table 14.

Table 14
EOC HRA with respect to large-scale applications: status and outlook

Scope	Study
Large-scale EOC identification; no quantification	Borssele EOC HRA, Dutch PSA, 2-loop 480 MWe PWR [50,51]
Large-scale EOC identification; small-scale quantification with first generation method	EOC pilot study, Swiss reference PSA, PWR [20]
Large-scale EOC identification; small-scale EOC quantification with second generation method	Outstanding (short-term milestone)
Large-scale EOC identification; large-scale quantification with second generation method	Outstanding (medium-term milestone)

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