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Abbreviations

AFW	auxiliary feedwater
ASEP	Accident Sequence Evaluation Program
ASME	American Society of Mechanical Engineers
ATHEANA	A Technique for Human Event ANAlysis
CAHR	Connectionism Assessment of Human Reliability
CBDT	Caused-Based Decision Tree
CCW	component cooling water
CDF	core damage frequency
CESA	Commission Errors Search and Assessment
CICA	Caractéristiques Importantes de la Conduite Accidentelle
CPC	common performance condition
CR	control room
CREAM	Cognitive Reliability and Error Analysis Method
CSF	critical safety function
EdF	Electricité de France
EFC	error-forcing context
EFW	emergency feedwater
EOC	error of commission
EOO	error of omission
EOP	emergency operating procedure
ESDE	excessive steam demand event
FW	feedwater
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH
GTRN	general transient
HEART	Human Error Assessment and Reduction Technique
HEP	human error probability
HFE	human failure event
HPSI	high pressure safety injection
HRA	human reliability analysis
IE	initiating event
IF	instrumentation failure
KAERI	Korean Atomic Energy Research Institute
LOCA	loss of coolant (accident) IE
LPI	low pressure injection
MDTA	Misdiagnosis Tree Analysis
MERMOS	Méthode d’Evaluation de la Réalisation des Missions Opérateur pour la Sûreté
misc.	miscellaneous
MOV	motor-operated valve
NARA	Nuclear Action Reliability Assessment
NPP	nuclear power plant
NR	narrow range (SG level)
NRC	US Nuclear Regulatory Commission
OE	operator error
OECD	Organization for Economic Co-operation and Development
PD	plant dynamics
PORV	pilot-operated PZR relief valve
PRA	probabilistic risk assessment
PSA	probabilistic safety assessment
PSF	performance shaping factor
PSI	Paul Scherrer Institut
PWR	pressurized water reactor
PZR	pressurizer
RAW	risk achievement worth
RCP	reactor coolant pump
RCS	reactor coolant system
RWST	refueling water storage tank
SCM	sub-cooling margin
SG	steam generator
SGTR	steam generator tube rupture
SI	safety injection
SLOCA	small LOCA
STA	shift technical advisor
THERP	Technique for Human Error Rate Prediction
UA	unsafe action
US	United States

Abstract

Illustrated by specific examples relevant to contemporary probabilistic safety assessment (PSA), this report presents a review of human reliability analysis (HRA) addressing post-initiator errors of commission (EOCs), i.e. inappropriate actions under abnormal operating conditions. The review addressed both methods and applications. Emerging HRA methods providing advanced features and explicit guidance suitable for PSA are: *A Technique for Human Event Analysis* (ATHEANA, key publications in 1998/2000), *Méthode d'Evaluation de la Réalisation des Missions Opérateur pour la Sûreté* (MERMOS, 1998/2000), the EOC HRA method developed by the *Gesellschaft für Anlagen- und Reaktorsicherheit* (GRS, 2003), the *Misdiagnosis Tree Analysis* (MDTA) method (2005/2006), the *Cognitive Reliability and Error Analysis Method* (CREAM, 1998), and the *Commission Errors Search and Assessment* (CESA) method (2002/2004). As a result of a thorough investigation of various PSA/HRA applications, this paper furthermore presents an overview of EOCs (termination of safety injection, shutdown of secondary cooling, etc.) referred to in predictive studies and a qualitative review of cases of EOC quantification. The main conclusions of the review of both the methods and the EOC HRA cases are: (1) The CESA search scheme, which proceeds from possible operator actions to the affected systems to scenarios, may be preferable because this scheme provides a formalized way for identifying relatively important scenarios with EOC opportunities; (2) an EOC identification guidance like CESA, which is strongly based on the procedural guidance and important measures of systems or components affected by inappropriate actions, however should pay some attention as well regarding EOCs associated with familiar but non-procedural actions and EOCs leading to failures of manually initiated safety functions. (3) Orientations of advanced EOC quantification comprise a) modeling of multiple contexts for a given scenario, b) accounting for shortcomings in context identification and evaluation, c) providing concise and effective guidance for the identification of adverse contexts, 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 judgments, e) addressing cognitive demands and tendencies, f) applying a simple discrete scale on the correlation between qualitative findings and error probabilities, g) using screening values for initial quantification, and h) aiming at data-based EOC probabilities by means of advanced event analysis techniques. Further development work should be carried out in close connection with large-scale applications of existing EOC HRA approaches.

Keywords: *error of commission, human reliability analysis, HRA methods, error identification, human error probability (HEP)*

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1. Introduction

1.1. Errors of commission in PSA

In terms used in nowadays probabilistic safety or risk assessment (PSA/PRA), an error of omission (EOO) is a human failure event (HFE) that results from inaction, and an error of commission (EOC) is a HFE that results from the performance of an action (ASME, 2002, Section 2, p. 8; NUREG-1792, 2005, p. 6-1). There is a lack of coverage of EOCs in the accident sequence models in nuclear power plant (NPP) PSAs. According to recent standards, it is not a requirement to explicitly address EOCs in post-initiator HRA (e.g. ASME, 2000; NRC RG 1.200, 2004; BfS, 2005). Nevertheless, the NRC report on *Good HRA Practices* recommends that future HRA/PSAs do attempt to identify and model potentially important EOCs (NUREG-1792, 2005, p. 2-2).

As shown in a number of compilations of incidents and accidents (e.g. NUREG-1624, 2000), EOCs do occur and contribute to failures of components or systems which are highly reliable from the hardware perspectives. Even relatively unlikely EOCs can have significant impacts. The implication is that there is a potential of misleading PSA results if EOCs are out of the scope. The profile of accident contributions may significantly change with the inclusion of EOCs. However, methodological problems are hindering EOC inclusions in PSA practice.

The EOC identification problem is closely associated with the concern of many practitioners that the *number of potential operator actions that could result in an EOC is unmanageably large* (NUREG-1792, 2005, p. 6-1). In EOC quantification, there is a stronger need to explicitly model specific decision errors leading to the specific inappropriate action in question, and to account for respective correlations between situational features and tendencies of human behavior. 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 (Dougherty, 1993).

1.2. Background, objective and overview

On the basis of the review of the state-of-the-art up to 1999 (Reer et al., 1999), the HRA project of the *Paul Scherrer Institute* (PSI) developed the *Commission Errors Search and Assessment* (CESA) method and carried out a large-scale pilot application of it, which showed the method to be feasible and effective in identifying plausible EOC opportunities (Dang et al., 2002; Reer et al., 2004). As an interim choice, the *Technique for Human Error Rate Prediction* (THERP) (Swain, Guttmann, 1983) was used for quantification in this pilot study. This experience, as well as the experience with other EOC analyses, showed that the EOC quantification remains an issue.

Undergoing PSI research (Dang, Reer, 2002; Reer, 2004a; Reer, 2004b) led to an outline of an advanced method for EOC quantification and a test application of it addressing two EOC HRA cases (Reer, Dang, 2006a; Reer, Dang, 2006b; Reer, 2006). A second pilot study is planned on a large-scale EOC HRA using the CESA method including an advanced quantification module to be elaborated on the basis of the method outline developed so far. As one of the first preparatory steps, a review of EOC HRA methods and applications was carried out including the identification of: potential improvements of the CESA method, advanced quantification concepts of other methods, and EOC-contributing factors predicted in existing quantification cases. The review is intended to inform analysts and researchers aiming at a comprehensive identification and quantification of EOCs in PSA studies. Note existing reviews of that type (or respective compilations of the HRA methods and applications) are rather old (e.g. OECD, 1998; OECD, 2000) or put too little emphasis on the EOC problem (e.g. NUREG-1842, 2006).

Section 2 presents a review of EOC identification methods and results. A review of EOC quantification methods and cases is presented in Section 3. Finally, a high-level summary of the methods and conclusions for EOC HRA are presented in Section 4.

Note *EOC identification* is understood here as the process leading to those HFEs that result from the performances of inappropriate actions. And the identification of adverse conditions for a given HFE is treated under the heading of *HFE analysis and quantification*.

In this report, the distinction between first and second generation HRA methods is frequently made. Historically spoken, the second generation comprises advanced developments undertaken in response to directive publications on context and human reliability and reviews of respective shortcomings in HRA practice (Dougherty, 1993; Cooper et al., 1996; Mosneron-Dupin et al., 1997). Speaking in more technical terms, the second generation includes features like:

- more detailed models of decision-based or cognitive errors (opposed to 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.

2. EOC identification

Section 2.1 summarizes the findings from the review of emerging methods for EOCs presented in (Reer et al., 1999; Dang et al., 2000). Section 2.2 presents a review of recent developments. EOC identification results, based on a review of the PSA/HRA literature, are compiled in Section 2.3. Finally, Section 2.4 summarizes the methods, and gives recommendations for EOC identification in PSA.

2.1. State-of-the-art up to 1999

One of the first steps of the PSI work in this area was an evaluation of the emerging methods for EOC analysis (Reer et al., 1999; Dang et al., 2000). In a cooperation with GRS, the evaluation and comparison addressed

- the Borssele screening methodology (Julius et al., 1995; Versteeg, 1998),
- the *Connectionism Assessment of Human Reliability* (CAHR) method (Sträter, 1997; Sträter, Bubb, 1999) method,
- the *Conclusions from Occurrences by Description of Actions* (CODA) method (Reer, 1997, 1999),
- the ATHEANA method as described in the draft report (NUREG-1624, 1998), and
- the *Cognitive Reliability and Error Analysis Method* (CREAM) (Hollnagel, 1998).

The methods apply a variety of approaches to identify EOCs. The evaluation identified three basic search schemes, in which the following search elements can be distinguished: actions (tasks), system failures, and scenarios.

The combinations of the search elements (actions, system failures, and scenarios) in the different schemes are illustrated in Fig. 2-1.

As summarized in (Dang et al., 2000), these schemes are:

- **Search for decision failures in procedures** (and consequent EOCs) (Borssele-global misdiagnosis search). This scheme is based on the fact the procedures to which the operators are directed will potentially influence all of the subsequent response. This scheme starts with the scenario. The procedure decision points that transfer operators to different procedures are reviewed qualitatively, in terms of the potential for an inappropriate transfer, and the inappropriate actions that result from these transfers, i.e. the actions that are demanded in the procedure that is erroneously transferred to, are considered. This scheme corresponds to **scenario-action-system** in Fig. 2-1.
- **Search for EOCs that fail required system functions** (ATHEANA, Borssele-local search). This scheme starts with the required system functions in the PSA model and searches for opportunities or motivations for the operator to commit actions that fail these functions. In other words, the EOCs are viewed as a failure mode for a system function that is additional to the hardware contributions. In ATHEANA, both external factors that distort the available plant indications (e.g. instrumentation failure or inadequacies) as well as internal factors that distort the interpretation of the plant indications are considered as potential motivations. This scheme corresponds to **scenario-system-action** in Fig. 2-1.
- **Search for situations where an action that is required in another context is inappropriate**, leading to a system failure (CODA). This scheme begins by identifying the key actions required in various accident scenarios and the objectives

of these actions, i.e. the goal states for the system or plant. For each such action and associated objectives, the accident sequence models are searched for situations in which this action is inappropriate. For example, alignment for recirculation from the containment sump is a required action in large loss of coolant accidents (LOCAs). The search should identify LOCA variants where there is no or insufficient water in the sump. (**action-system-scenario** in Fig. 2-1.)

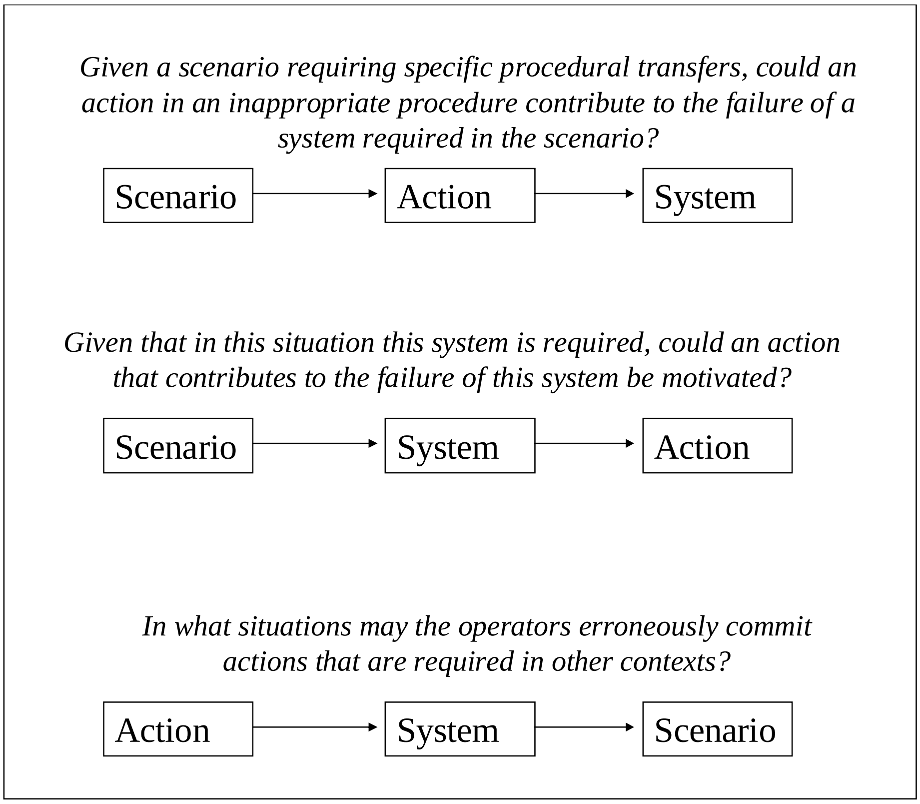

Fig. 2-1. Schemes for EOC identification (by looking at adverse combinations of three key elements)

Some methodologies, e.g. CAHR and CREAM, do not propose a specific scheme for identifying potential EOCs. For instance, the CREAM methodology relies on the preceding event sequence model (as is done in PSA) to identify the opportunities for decision and/or execution failures that would lead to EOCs.

Following the review of emerging EOC methods, the CESA method was developed with the explicit aim to identify potential EOC scenarios that could be risk significant (Dang et al., 2002; Reer et al., 2004). The method expressly addressed the additional contribution from EOC scenarios to the risk assessed in a typical industrial PSA study. In terms of the search schemes mentioned above, CESA's basic identification scheme is an *action-system-scenario* scheme. It proceeds from actions (identified from procedures and related training) to the affected systems to scenarios. It is closest to the CODA search scheme and integrates elements of the other schemes.

2.2. Recent developments (since 1999)

The literature review covering the years from 2000 to 2006 identified four methods addressing EOC identification in PSA, (1) the 2000 version of the ATHEANA method (NUREG-1624, 2000), (2) the GRS EOC HRA method (Fassmann, Preischl, 2003), (3) the

MDTA method developed by the *Korean Atomic Energy Research Institute* (KAERI) (Kim et al., 2005, 2006a, 2006c), and (4) the CESA method developed at PSI (Dang et al., 2002; Reer et al., 2004).

2.2.1 The ATHEANA method (state of 2000)

Method summary. The ATHEANA method is the result of development efforts sponsored by the US Nuclear Regulator Commission (NRC) (Cooper et al., 1996; NUREG-1624, 1998, 2000). Fig. 2-2 presents the steps related to EOC identification according to the 2000 version of the ATHEANA method (NUREG-1624, 2000). The analyst is guided to look for unsafe acts that can fail system functions required in a scenario. Scenario identification and prioritization relates to the definition of the scope of analysis. To support this step, the method provides a list of nine accident sequence characteristics (Table 2-1) that have potentially high risk from the human perspective. In the next step, the *base case scenario* is described, which represents the most realistic description of the expected plant and operator behavior for the selected initiator. HFEs (including EOCs) are identified on the basis of the functions that have to be performed by the systems involved in the base case scenario. For each function, possible functional failure modes have to be identified and the opportunity for errors of omission or commission involving that failure modes have to be evaluated.

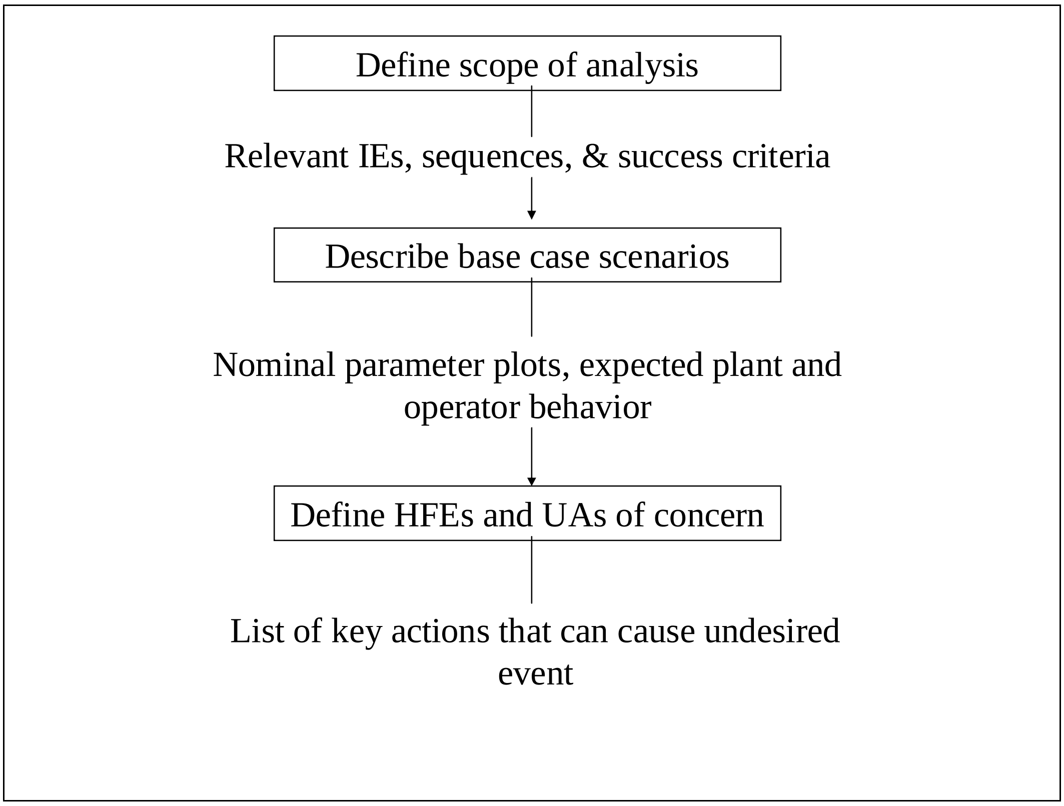

Fig. 2-2. ATHEANA steps related to EOC identification
Source: NUREG-1624, 2000, Fig. 6.1 (excerpts).

Table 2-1. ATHEANA-suggested characteristics of high priority initiators or accident sequences (NUREG-1624, 2000, Table 9-2)

Characteristic of scenario	Comment/example
1. Short time to damage	Large-break loss-of-coolant accident (LLOCA) initiator
2. Unfamiliar	Not specifically analyzed in FSAR (final safety analysis report), not specifically included in operator training
3. Single functional failure goes to damage	Long-term cooling (e.g. failure of changeover to recirculation mode) in scenarios requiring this function
4. Distraction that separates CR team	Fire requires someone from the CR staff to function as a fire-fighting crew member
5. Forces independent action by one member of team	Fast response required with little time for stepwise communication
6. Potential for complex and/or hidden or unfamiliar conditions	No salient evidence or reminders; dependencies or dependent failures, especially where cause and effects are far removed from each other; confusing secondary (PWRs) or support system failures; fires; seismic events
7. Multiple (maybe conflicting) priorities	Operators must select among or use multiple procedures (or other rules)
8. Wide range of accident responses, plant dynamics/conditions represented	Confusion with similar but less complex situation
9. Relatively high-frequency events	Transients, SLOCA

Comments. Basically, the EOC search in the 2000 version (NUREG-1624, 2000) of ATHEANA works in the same manner as in the 1998 version (NUREG-1624, 1998). There are differences in the wording used. And four additional characteristics for scenario prioritization are presented (Table 2-1, nos. 2, 4, 5 and 7).

A critical issue associated with ATHEANA is still holding: the method does not present a formalized way for scenario identification. The prioritization characteristics cover a wide spectrum of scenarios and thus leave much flexibility to the analyst. It is difficult to imagine a post-initiator scenario to which none of the characteristics in Table 2-1 applies. Besides, the characteristics are difficult to assess out of the context of a specific HFE in mind. According to the method guidance (Fig. 2-2) however, such assessments are supposed to prepare HFE identification.

It is a positive feature that the ATHEANA process is illustrated by examples closely related to contemporary PSA. In this context, it is worthwhile noting that one of the examples presented in the 2000 ATHEANA version suggests a flexible treatment of the sequence of steps presented in Fig. 2-2: an action (*back-throttling or shutdown of secondary cooling flow*) is defined first, and a relatively important scenario (in which this action would be an EOC) is identified subsequently (NUREG-1624, 2000, App. B). Note this process matches the sequence of analysis steps suggested by the CODA method (Reer, 1997, 1999, 2000) and implemented in the CESA method (Dang et al., 2002; Reer et al., 2004).

2.2.2 The GRS method

Method summary. The GRS method (Fassmann, Preischl, 2003) presents guidance for the identification and quantification of operator behavior denoted as *schädlicher Eingriff* (in German); this term is translatable as *aggravating intervention* and thus in compliance with the definition of EOC according to the state-of-the-art terminology (e.g. NUREG-1792, 2005). In this sense, the scope of EOCs addressed comprises operator actions characterized as follows:

(1) *They belong to operating, testing or emergency operating procedures operators are well acquainted with from instruction, simulator training, and/or practice.*

(2) *Performance of the actions would cause negative consequences in scenarios studies in level-1 and level-2 PSA.*

(3) *From a technical point of view action performance is nevertheless possible. …*

(4) *Actions can be performed with the means provided by the interfaces in the main control room and in the emergency control room* (Fassmann, Preischl, 2003, p. iii).

The proposed EOC search process is presented in Fig. 2-3. It is recommended to determine the plant situation to be assessed within the scope of event sequence and system analyses. The respective search should consider event sequences

- leading to core damage and becoming essentially more likely if EOCs are accounted for;
- leading to stable plant state without EOCs and becoming relevant contributors to the core damage frequency (CDF) in case of EOC inclusion;
- providing sufficient intervention options (timing and possibilities of resetting of automatic devices).

For such a situation, the analysis proceeds with the identification of the needed system functions together with the status of alignment of systems and components required to maintain the safe operation of these functions. A credible EOC is considered if an operator action can jeopardize or disable such a function and if the respective intervention can be carried out in the normal or emergency control room (CR) meaning local actions are out of the analysis scope.

The technical possibility of the intervention is assessed regarding automatic devices that may hinder it (in the sense of an interlock). In case of such an 'intervention-hindering' device, the EOC is retained if the device can be disabled by an action in the normal or emergency CR; the EOC is screened out otherwise.

It is guided to retain only those EOCs associated with interventions that are familiar to the operator in the context of situations, in which it is required to change the system/component state in a comparable manner. Review of written material (procedures, shift logbooks, system handbooks, training plans, and the like) and interviews with plant experts are recommended as the information sources to be used for this 'familiarity' assessment.

For a potential EOC retained, an *operator model* is compiled on the likely course of man-machine interactions in the respective situation. The model includes information about the plant state, available personnel, procedures, and tasks (outstanding, under performance, finalized). Finally, the boundary conditions of the further EOC analysis are defined: intervention goal, concurrent goal, initiation and termination criteria of the intervention, required intervention time, time available for correction, intervention control, redundant information, success-supporting information.

Comments. The GRS EOC search scheme is close to the one of the ATHEANA method. For a given scenario (denoted as *plant situation* in the GRS method), it is assessed whether a human intervention can contribute to the failure of an important system function that is required in the scenario; see Fig. 2-1, *scenario-system-action*. It is a positive feature that EOC identification criteria are explicitly defined. The criteria themselves are reasonable:

- The assumption that operators might inhibit an automatic signal (which hinders the EOC) may be debatable but is reasonable in view of a number of EOCs in nuclear operating experience (c.f. the compilation in Kauffman, 1995).

- Retaining only familiar interactions (known to the operator from acceptable contexts) is reasonable to keep the analysis on a credible level. GRS's criterion for *familiar* is close to the one proposed in the CESA method (Dang et al., 2002; Reer et al., 2004), in which actions known from procedures or training define the scope of plausible intervention options.
- The non-consideration of local interventions may be debatable (especially due to the envisaged coverage of level-2 PSA). However, the assumption must be seen as a scope limitation of interim nature (meaning an extended method version may address local EOCs as well).

As the ATHEANA method, the GRS method does not present a formalized way for the identification of scenarios to be addressed in the search for EOC opportunities. The proposed criteria for scenario selection refer to EOCs to be identified. The notions used indicate strong reliance on the expertise of the accident sequence and system analysts.

Another critical issue of the GRS method is the lack of illustration linked to HRA/PSA practice. The method report (Fassmann, Preischl, 2003) contains 216 pages. An application example relevant to contemporary PSA is not presented.

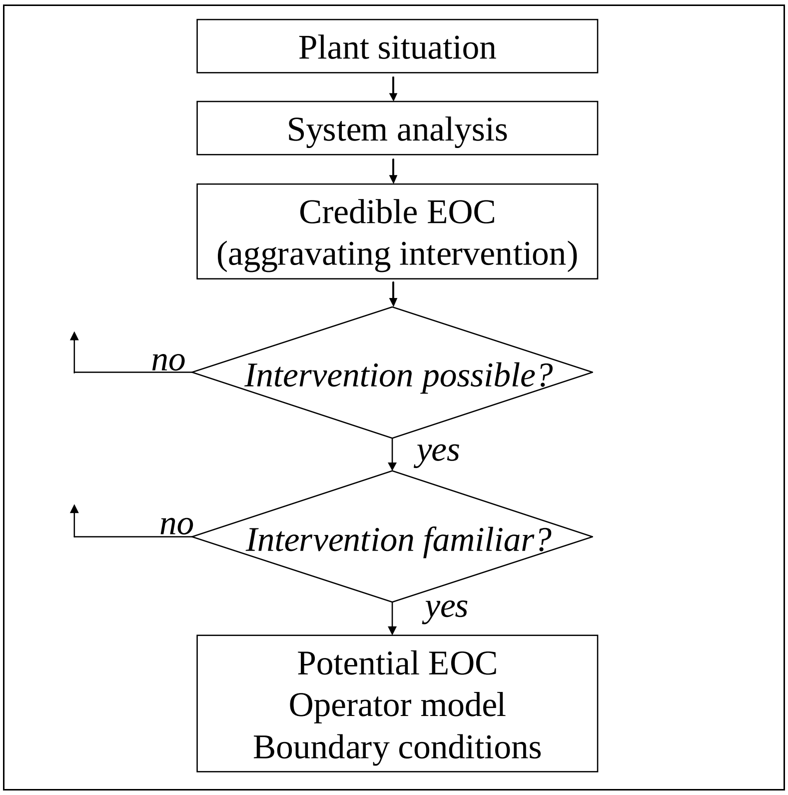

Fig. 2-3. Process of EOC identification in the GRS method
Translated from: Fassmann, Preischl, 2003, Fig. 5-3.

2.2.3 The MDTA method

Method summary. A summarized description of the MDTA method is presented in (Kim et al., 2006a). Detailed descriptions with emphases on EOC identification and quantification are presented in (Kim et al., 2005) and (Kim et al., 2006c), respectively.

For a given post-initiator scenario, the method serves to identify and quantify human failure events (HFEs), i.e. inappropriate actions (EOC HFEs) or failures of required actions (EOO HFEs), induced by misdiagnoses. The analysis process is mainly driven by the structure of the emergency operating procedures (EOPs). It is assumed that the operator performs the diagnosis EOP in a step-by-step fashion and that there is a tendency to maintain an initial diagnosis. The method has three main steps: (1) Assessment of the potential for diagnosis failures; (2) Identification of the HFE (EOC and/or EOO) that might be induced due to diagnosis failures; and (3) Quantification of the HFEs and their modeling. Steps (1) and (2) are summarized next, while step (3) is summarized in Section 3.2.3.

To identify diagnosis failures for a given scenario, a **misdiagnosis tree** (see Fig. 2-4) is compiled with the procedural decision rules (or criteria)[1] as headers and the final diagnoses as end states. In connection with each decision criterion presented in the header, the analyst is guided to consider three types of contributors to diagnosis failures.

(i) *Plant dynamics* (PD): mismatch between the values of the plant parameters and the decision criteria of the diagnostic rule of the EOP due to dynamic characteristics. For instance, *inadequate sub-cooling margin (SCM)* is a decision criterion in the diagnosis EOP. This criterion is identified as relevant for the response to a small loss of primary coolant (SLOCA) defined for leak sizes from 0.38 to 1.91 inch: the EOP is likely to guide the correct diagnosis of a LOCA in case of *inadequate SCM* (see Kim et al., 2006c, Fig. 3). Thus a SLOCA variant, in which the SCM is adequate due to a relative small leak size (0.38 to 1.5 inch), is modeled as a diagnosis failure contributor of type PD (Fig. 2-4).

(ii) *Operator error* (OE): errors during information gathering or rule interpretation. According to the examples provided in (Kim et al., 2005), the following qualitative results on OE assessment are possible: (a) both types of errors apply (information gathering and rule interpretation error) apply, (b) one of the error types applies, or (c) both error types are negligible.

(iii) *Instrumentation failure* (IF): problems in the information system; e.g. *pressure transmitter drifts high.*

In that way the misdiagnosis tree displays paths leading to a final diagnosis, which is usually described in terms of an initiating event (IE).[2]

To identify HFEs for a given misdiagnosis, the required functions (requisite from the PSA viewpoint) of the actual event are compared with the ones in the misdiagnosed event. An EOC HFE is identified as follows.

- An unsafe action (UA) related to a required function is identified if the EOP corresponding to the misdiagnosis provides an option for terminating a function required by the actual event.
- An UA related to a non-required function is identified if this function is required by the misdiagnosed event and if its initiation has an impact on plant safety in the actual event.

The UA is assumed with a probability of 1 if the criteria for function termination or initiation are satisfied in the EOP corresponding to the misdiagnosis. Otherwise, a conditional UA probability in the range from 0.05 to 0.1 is recommended.

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[1] According to the method description, the headers in the misdiagnosis tree are denoted as *decision rules* (Fig. 2 in Kim et al., 2006a). In the HRA example however, decision criteria are used (see Fig. 2-4 in this report).

[2] In the MDTA method, it is possible as well that a misdiagnosis is expressed as success or failure with respect to the identification of a critical system state; e.g. the state associated with HPSI throttling criteria in a station blackout scenario (Kim et al., 2005, Section 4.3).

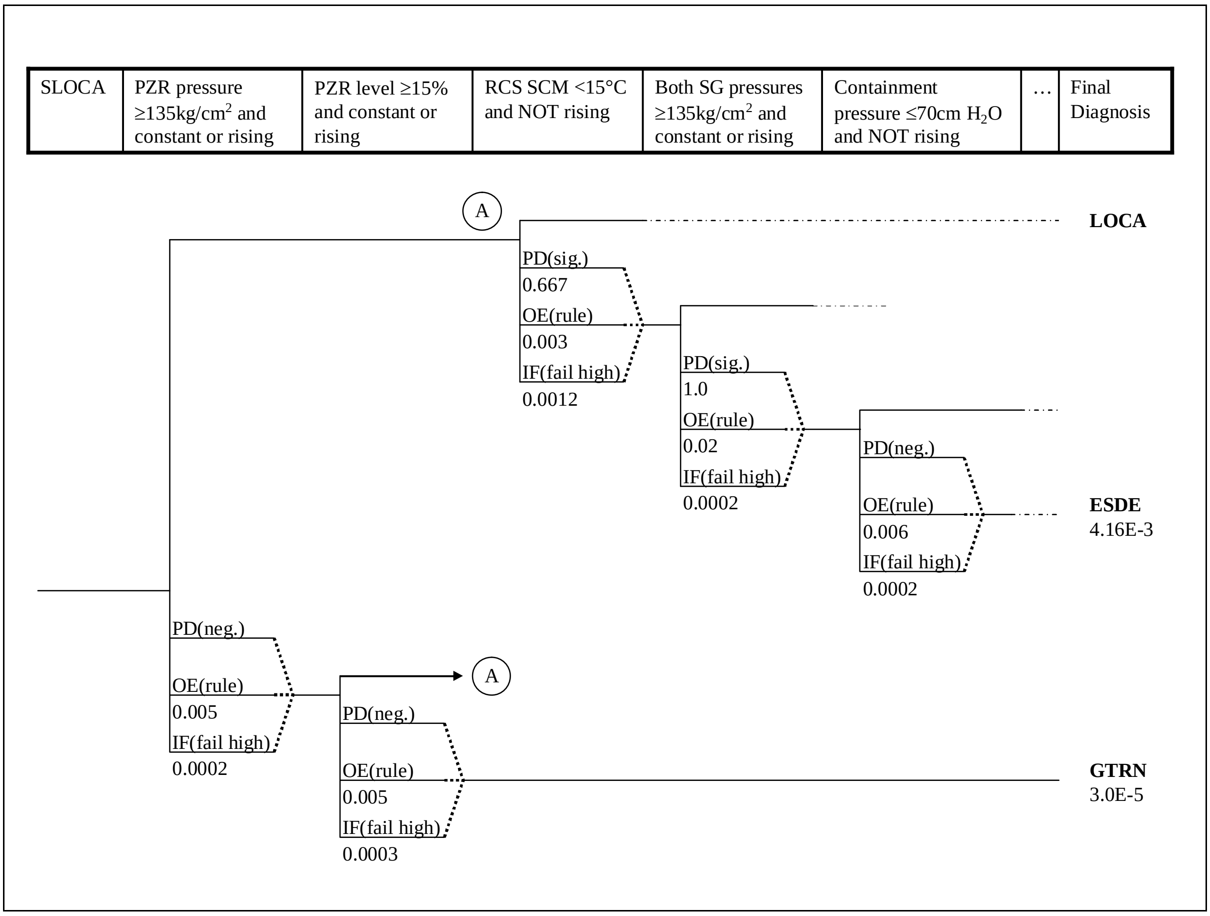

Fig. 2-4. Excerpts from a misdiagnosis event tree developed for a SLOCA event
Source: Kim et al., 2006c.
Legend (compiled by the reviewer)
PD(neg.): adverse decision (*) due to plant dynamics is negligible.
PD(sig.): adverse decision (*) due to plant dynamics is a significant failure contributor.
OE(rule): adverse decision (*) due to operator error in rule interpretation.
OE(infvrule): adverse decision (*) due to operator error in information gathering or rule interpretation.
IF(fail high): adverse decision (*) because relevant instrumentation fails high.
LOCA: loss of primary coolant event (correct diagnosis).
ESDE: excessive steam demand event (misdiagnosis).
GTRN: general transient event (misdiagnosis).
(*) Note the term *adverse decision* is used here to circumvent the debate whether a response that is instructed by the procedure (e.g. in case that the SCM is adequate, i.e. above 15°C, due to a small leak size) and that contributes to a misdiagnosis on the other hand should be classified as an inappropriate decision.

Comments. The MDTA method is an important step forward in implementing advances in HRA, namely accounting for EOCs and addressing specific causes of decision errors. It is especially appreciated that the analysis process is illustrated by cases relevant to contemporary PSA.

The EOC identification process in the MDTA method is similar to the global misdiagnosis search in the Borssele method (Julius et al., 1995), i.e. search scheme *scenario-action-system* in Fig. 2-1. EOPs are analyzed to identify misdiagnosis paths and associated actions leading to failures of required systems (or functions). Misdiagnosis contributors OE and IF are explicitly referred to in the guidance of both methods. MDTA adds contributor PD. The

Borssele method (1) explicitly refers to equipment failures that can produce misleading indications, and (2) presents guidance for IE selection[3]; MDTA does neither (1) nor (2).

The MDTA method guidance puts too much emphasis on scenarios defined in terms of IEs. Adaptations would be required to address a scenario defined as a combination of an IE with a set of system failures.

For an analyst preferring a search scheme starting with scenarios defined by IEs, the misdiagnosis tree (proposed in the MDTA method) is a useful tool for identifying diagnosis failure paths and documenting the analysis process. Note the concept of misdiagnosis paths is similar to the concept of EOC paths in the CESA method (Reer et al., 2004; Reer, Dang, 2007).

From the qualitative viewpoint, the essential difference is that CESA defines operator actions as endpoints, while MDTA defines diagnoses as endpoints and thus needs to identify in a second stage the induced HFEs.

Denoting a diagnosis as *final* might be a problematic issue, since a diagnosis is usually subject to revisions throughout the process of procedure following. Given a package of symptom-based procedures, it is even difficult to specify a diagnosis in terms of an IE. Furthermore, the specification is somewhat depending on the concept of IE modeling of the PSA in question. For instance, the PSA may include a separate IE denoted as *inadvertent start of HPSI*. In this case, this IE should be assigned to the endpoint denoted as *GTRN* in Fig. 2-4.

Another commonality between MDTA and CESA is the emphasis on procedural actions in the EOC identification process. In that way, the MDTA supports the argumentation that procedural orientation is a reasonable starting point for establishing EOC analysis in HRA practice (Reer et al., 2004).

More support and clarification is required with respect to the MDTA assumption of an increased UA probability (0.05 to 0.1) for the case that the plant conditions for an UA do not satisfy the rules in the inappropriate EOP taken due to misdiagnosis. It needs to be clarified why this increased HEP is proposed and whether it can be applied to any action mentioned in the inappropriate EOP. Note the CESA method would define for these plant conditions a separate EOC path element to be addressed by quantification. A reduced HEP is expected, given these plant conditions are different from the ones related to the rule that provides the option for the transfer to the inappropriate EOP. Since dependence has to be taken into account in any case, a HEP in the range from 0.05 to 0.1 appears to be reasonable.

2.2.4 The CESA method

The CESA method was developed with the goal to provide a tool for EOC identification in PSA practice. The first publication is in (Dang et al., 2002). Currently, the main publication on the CESA pilot study is (Reer et al., 2004); a report describing the method in the form of user guidance has been recently published (Reer, Dang, 2007).

CESA's identification process complies with the CODA search scheme *(action-system-scenario)* illustrated in Fig. 2-1. The main reason for choosing the scheme was to have a formalized way for scenario identification and prioritization. Once a set of actions is defined by their consequences in terms of specific system states, two stages of screening become applicable. First, it is possible to screen on the basis of system failure importance measures, since the links between actions and system failures are deterministic. For a precisely defined action it

[3] However, Borssele's IE selection guidance is de facto ineffective. It is advised to screen out IEs with a frequency that is two orders of magnitude less likely than the CDF (Julius et al., 1995, p. 195); e.g. given a CDF of 10^{-5}/a, all IEs with a frequency above 10^{-7}/a would retain (which is nearly 100% in contemporary PSA studies).

can be determined explicitly whether it would result in a fault tree top or basic event, and (if so) which. Second, it is possible to screen on the basis of scenario frequencies, since the links between system failures and scenarios are deterministic as well. It can be determined explicitly in which event sequences a given system failure is modeled. This points to relative likely scenarios in which an action may cause an important system failure (Reer et al., 2004, p. 201).

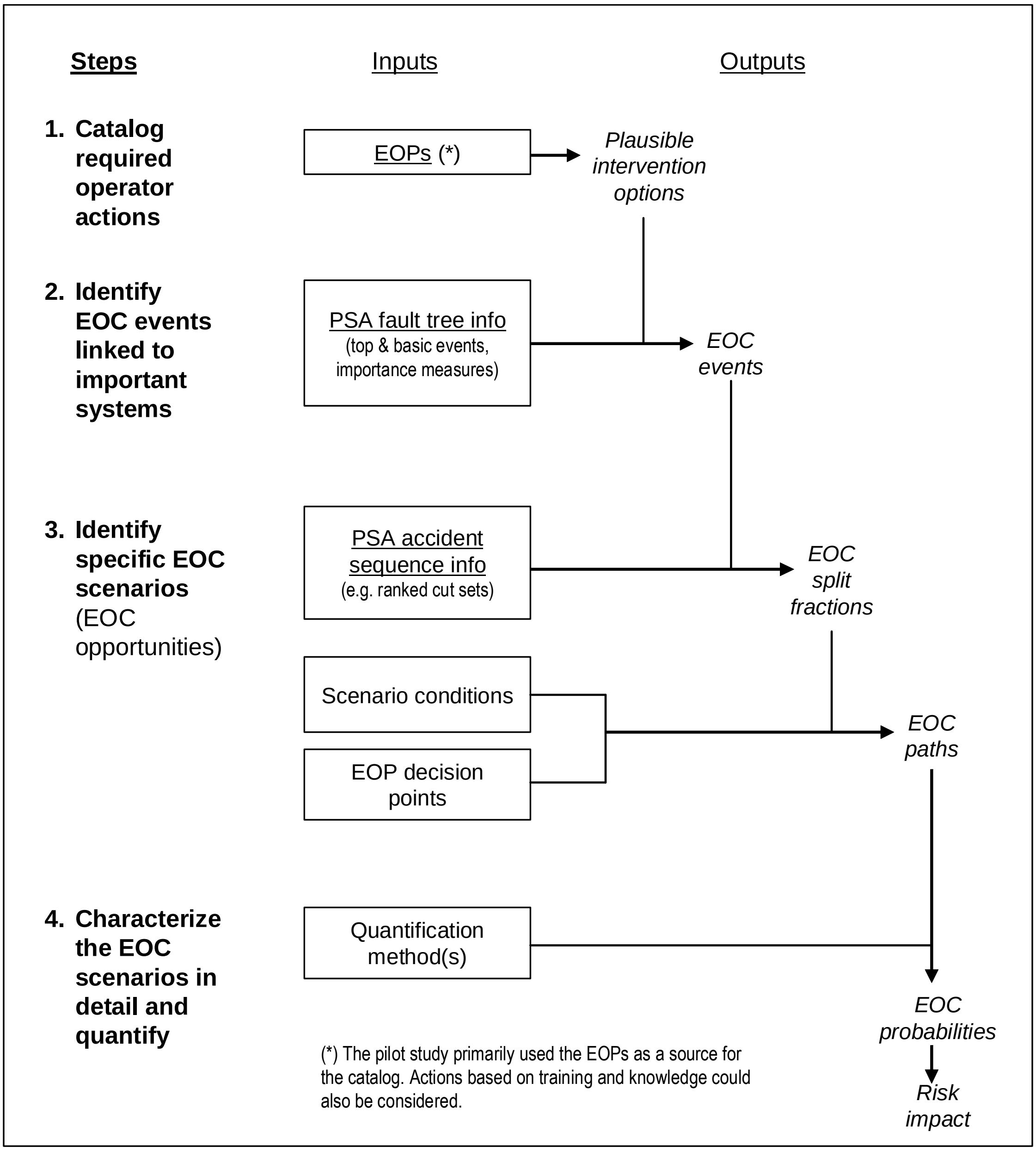

Fig. 2-5. Flowchart of the CESA steps

Method steps 1 to 3 in Fig. 2-5 serve the implementation of the CESA's search scheme. On the basis of emergency operating procedures and related practices (e.g. with respect to manipulations associated with a procedural task), possible actions are selected and cataloged in step 1. The result is a plausible set of intervention options (i.e. credible possibilities for human-induced changes of system states).

Step 2 deals with the identification of system failures (or degradations) that may result from these actions. Prioritization of system failures is mainly performed on the basis of the importance measures of the PSA top or basic events for these system failures. It is recommended to use the risk achievement worth[4] (RAW) for this purpose. For instance, the identification may focus on the PSA top (or basic) events with RAW>10. Each combination of a PSA top or basic event with a procedural action (that would contribute to the failure of this event) defines an EOC event, i.e. an operator action that may contribute to a system failure in some - at this point unspecified - scenarios.

On the basis of the accident sequences in the original PSA model, the scenarios in which an EOC event may occur are identified in step 3. It is recommended to focus on event sequences with a relatively high frequency. Event sequences that have similar performance conditions are grouped, and each group is defined as a scenario with the opportunity of the EOC event in question. The combination of an EOC event with a group of similar event sequences defines an EOC split fraction, i.e. an operator action that contributes to a system failure in a specific scenario. At this point, the specific scenario evolution and personnel responses that lead to the performance of the inappropriate action have not been determined. For each EOC split fraction, the procedural decision points and the scenario conditions corresponding to the branching criteria are analyzed, in order to identify the EOC paths.

2.3. EOC prediction results

A review of sources on PSA/HRA applications identified a variety of EOC prediction results. The sources are presented in Section 2.3.1 and the EOCs in Section 2.3.2.

2.3.1 Sources involving EOC predictions

The open literature on PSA and HRA issues was examined with the goal to identify EOCs predicted so far in scenarios during full-power operation of NPPs. Only sources involving EOC predictions for NPPs of type PWR were identified. In Table 2-2 the sources are grouped under three headings and briefly characterized. Three sources comprise comprehensive applications (large-scale) of EOC identification methods (*Borssele*, CESA, ATHEANA). Five sources are PSAs that include EOCs presumably identified - from accident sequence analysis, HRA, and task analyses supporting the HRA - without a specific EOC identification method: it is unclear (from the indicated references) to what degree EOCs were systematically identified; the applied HRA methods do not cover the process of HFE identification. And three sources are examples and descriptions (small-scale applications of methods). The table reflects the lack of coverage of EOCs in PSA practice. Only three sources involve large-scale applications in which systematic EOC identification has been reported.

2.3.2 EOC types from the system function perspective

The MDTA method distinguishes between two functional EOC types, (1) termination of a function (which is required and ‘running’), and (2) initiation of a function (which is inappropriate and not ‘running’). The review of HRA applications and operational events (Reer, 2004b) showed that this classification may require extension. At least, the *inhibition of a function* (required and not ‘running’ so far) needs to be added. Furthermore, it would be worthwhile to separate between the terminations of (a) automatically initiated or normally operating functions and (b) manually initiated functions, since the latter may be addressed already in the quantification of the respective EOO HFE and thus may not require separate

[4] The RAW is defined as the factor by which the CDF increases if the top (or basic) event is modeled with a failure probability of 1.0; c.f. ASME (2002).

treatment. In that way, Table 2-3 provides a structured presentation of EOCs predicted in PSA/HRA applications.

Most of the EOCs are terminations of automatically initiated or normally operating functions. Within this group, actions terminating safety injection (SI) (Table 2-3, EOC no. 1) and actions degrading secondary cooling (nos. 2-6) are common identification results in a number of PSA/HRA applications. Termination of bleed and feed operation by closing the pilot-operated pressurizer relief valve (PORV) and LOCA creation by PORV opening are common identification results in two studies.

Table 2-2. Sources (published PSA/HRA applications) involving EOC predictions in situations during full-power operation of NPPs

Sources	Remarks
Comprehensive applications (large-scale) of EOC identification methods	
(a) Borssele EOC HRA, Dutch PSA, 2-loop 480 MWe PWR (Versteeg, 1998; Julius et al., 1995)	The method outlined in Section 2.1 has been applied.
(b) EOC pilot study, Swiss reference PSA, PWR (Dang et al., 2002; Reer et al., 2004)	The CESA method has been applied (summary in Section 2.2.4).
(c) Pressurized thermal shock (PTS) study, NRC project, US PWRs (Whitehead, Kolaczkowski, 2006)	An 'ATHEANA-driven' EOC search has been applied. The indicated reference does not present implementation details.
PSAs that include EOCs (presumably identified from accident sequence analysis, HRA, and task analyses supporting the HRA, without a specific EOC identification method)	It is unclear (from the indicated references) to what degree EOCs were systematically identified. The applied HRA methods do not cover the process of HFE identification.
(d) German PSA, PWR (BfS, 1997)	
(e) French PSAs, 1990, EPS 900 and 1300, PWRs (Lanore, 2000, 1998)	
(f) Finnish PSA, 1996, Loviisa 1, PWR (Vaurio, 1998)	
(g) British PSA, 1994, Sizewell B, PWR (Coxson, 1998)	
(h) French N4 PSA (PWR), MERMOS HRA (Bieder et al., 1998; Le Bot, 2000)	
Method examples and descriptions (small-scale applications)	The EOC identification methods are summarized in Section 2.2.1 and 2.2.3.
(i) ATHEANA HRA examples, US PWR (NUREG-1624, 2000)	
(j) ATHEANA trial application, Japanese 1100 MWe class 4-loop PWR (Fukuda et al., 2000; Fukuda, 2000)	
(k) MDTA method illustration, South Korean standard NPP (PWR), combustion engineering typed EOP system (Kim et al., 2005, 2006a, 2006c)	

Table 2-3. EOCs referred to in PSA/HRA applications

EOC (inappropriate action)	Sources (Table 2-2)		
	Comprehensive applications	PSAs that include EOCs	Method examples and descriptions
Termination of an automatically initiated or normally running function			
1. Termination or throttling of safety injection (SI) (*1)	(a) (b)(*2)	(e) (h)	(i) (k)
2. Back-throttling or shutdown of secondary cooling flow (*1) (*3)	(a) (b) (c)(*4)	-	(i)
3. Isolation of wrong SG (*1)	(a) (c)	-	-
4. Isolation of one SG (resulting in degraded secondary cooling) (*1)	(a)	-	-
5. Termination of AFW	(b)	-	(j)
6. Stop of special and emergency feedwater (EFW)	(b)	-	-
7. Isolation of SG relief valve	(c)	(e)	-
8. Opening of turbine bypass or atmospheric dump valves (creation of excessive steam demand)	(c)	-	-
9. Trip of reactor coolant pumps (RCPs)	(c)	-	-
10. Isolation of RCP cooling water supply (from RWST) (*5)	(b)	-	-
11. Disconnection of 120V DC buses	(b)	-	-
Termination of a manually initiated function			
12. PORV closing or SI stop (termination of bleed and feed in loss of FW scenarios)	-	(g)	(j)
13. PORV closing (termination of forced RCS cooling in SGTR scenarios)	-	-	(j)
Initiation of a function			
14. PORV opening (LOCA creation) (*1)	(a) (c)	-	-
15. Premature switchover to sump recirculation	-	(d)	-
16. Primary circuit dilution	-	(f)	-
17. Start of a RCP	(b)	-	-
Inhibition of a function			
18. Inhibition of EFW restart (*6)	(b)	-	-
19. Inhibition of start of primary CCW pumps	(b)	-	-

(*1) In source (a), this EOC was initially identified but finally screened out.
(*2) The Swiss pilot study identified more EOCs than the ones indicated by source (b). This table presents only those EOCs referred to in the references published so far. Note no quantification has been carried out for EOC nos. 11 and 19 in the pilot study.
(*3) In source (b), this EOC is element of EOC split fractions "FA*FB.EOC1" and "FN.EOC1" (Reer et al., 2004).
(*4) Source (c) does not present any EOC quantification.
(*5) In source (b), this EOC is element of various "RW.EOC" split fractions (Reer et al., 2004).
(*6) In source (b), this EOC is element of EOC split fraction "FN.EOC1" (Reer et al., 2004).

2.4. Summary and recommendations

2.4.1 EOC search schemes

Available methods for EOC identification on the level of HFEs are: Borssele (Julius et al., 1995; Versteeg, 1998), ATHEANA (NUREG-1624, 2000), GRS (Fassmann, Preischl, 2003), MDTA (Kim et al., 2005, 2006a, 2006c), and CESA (Reer et al., 2004; Reer, Dang, 2007). Comprehensive applications have only been reported for Borssele, ATHEANA (PTS) and CESA. Borssele, MTDA and CESA have in common that the EOC search is closely linked to the procedural guidance and thus shows a high degree of transparency.

Since the review carried in (Reer et al., 1999), the following methods are new developments: GRS, MDTA, and CESA. Furthermore, an updated version of ATHEANA has been published in 2000. Table 2-4 summarizes the characteristics of these emerging methods. Application examples relevant to contemporary PSA are provided for methods ATHEANA, MDTA and CESA.

Table 2-4. EOC HFE identification in second generation HRA methods

Method	Application example provided relevant to contemporary PSA?	Comprehensive (large-scale) application reported?	Search scheme (c.f. Fig. 2-1)	Main characteristics of the criteria for screening or prioritization
ATHEANA	Yes: Table 2-2, sources (i) and (j)	Yes: Table 2-2, source (c)	Scenario - System - Action	Qualitative: characteristics of high priority initiators or accident sequences; c.f. Table 2-1
GRS	No	No	Scenario - System - Action	Qualitative: familiarity and possibility (in CR) of EOC-related intervention; c.f. Fig. 2-3
MDTA	Yes: Table 2-2, source (k)	No	Scenario - Action - System	Quantitative: likelihood or possibility of 3 types of failure contributors (PD, OE, IF) per procedural decision point; c.f. Fig. 2-4
CESA	Yes: Table 2-2, source (b)	Yes: Table 2-2, source (b)	Action - System - Scenario	Quantitative: risk importance measures of EOC-related systems/components and frequencies of affected accident sequences; c.f. Fig. 2-5

Except for CESA, the EOC search in each method is supposed to start with a scenario: for a given scenario, it is guided to look for actions that are inappropriate. The review above (Sections 2.2.1-2.2.3) suggests this approach has shortcomings in providing a formalized way for scenario identification and prioritization. This problem is supposed to induce difficulties in a full-scope HRA of EOCs: a large number of IEs (a PSA model may comprise about 100 IEs) is possible, and a variety of systems is demanded in the IE evolution; each IE itself or in combination with additional failures defines a scenario the operators have to deal with.

As outlined in Section 2.2.4, the CESA method provides a way to overcome this problem by using a search structure starting with operator actions. CESA's limitation is that no other actions than the ones described in procedures for the post-initiator response and based on respective training are considered as EOC candidates. This limitation is however reasonable, in view of the restrictions on procedural actions made as well in the GRS method and in the MDTA method.

Nevertheless, GRS's familiarity criterion (Fig. 2-3) suggests addressing as well the EOC potential of non-procedural actions credited in the PSA as required. By default, a credited action is supposed to be familiar, regardless whether it appears in the procedure. Closures of valves required for the termination of internal flooding or LOCA events are typical non-procedural actions modeled as required in some PSA studies. Of course, most of the system-required actions are also required by the procedures meaning a catalogue of procedural actions would be completed only by a few records. Respective guidance is provided in the current CESA version (Reer, Dang, 2007). This version accounts as well for the implementation details presented in Section 2.4.2.

2.4.2 Implementation details

EOC prediction results (Table 2-3) were reviewed with the goal to assess whether they are identifiable by the CESA method. It is concluded that the EOCs would be retained in the screening process addressing a PSA of high quality (regarding systems and sequence modeling and EOO HRA), given that the associated system (or component) failure has a high risk importance (say RAW>10).

The review however identified two important details deserving attention in the implementation of an EOC identification method based on importance measures of systems or components (potentially) affected by inappropriate actions.

EOCs affecting groups of failure events. In a wider sense, this detail is associated with EOC no. 13 in Table 2-3. It comes into play if EOC screening is carried out on the basis of the important measures of the systems and components affected by inappropriate actions. The concern is:

- A failure event group, defined as the joint failure of two (or more) top (or basic) events, might have a high RAW, while each group element has a low RAW.
- And an EOC may affect the entire group (i.e. an action or set of actions required under a particular condition may lead to a state equivalent to the joint failure).

For instance, if the PSA models the failures of auxiliary feedwater (AFW) trains A and B as two different top events, the analyst is advised to: define the failure of *AFW trains A and B* as a top event group, and determine the RAW of this group for the purpose of prioritization. To identify such groups, it is recommended to scan through list of top event names and to review the structure of the event trees.

It is worthwhile noting that it is not always easy to identify groups of failure events that are functionally related with respect to EOC opportunities. Fig. 2-6 shows such a case: one HFE on depressurization of the reactor coolant system (RCS) - required in a SGTR scenario - is modeled in connection with two redundant hardware functions: pressurizer (PZR) spray, and PORV opening; each function provides an adequate option for RCS depressurization. This redundancy is supposed to drive down the RAW of each function meaning the RAW-based search may not identify *premature termination of RCS depressurization* as an important EOC.

To diminish this problem, the EOC HRA may address as well premature terminations of manually initiated functions (e.g. in Fig. 2-7). In this case however, the problem of double counting has to be taken into account.

Problem of double counting when addressing premature terminations of manually initiated functions. This problem is associated with EOCs nos. 12 and 13 in Table 2-3. Both EOCs are premature terminations of manually initiated functions, i.e. feed and bleed in loss of feedwater scenarios (EOC no. 12), and forced primary cooling in steam generator tube rupture (SGTR) scenarios with failure of isolation of the faulted SG (EOC no. 13). Each function is terminated if the PORV is closed.

The identification of such kinds of EOCs is important on the one hand but would be dispensable if the EOO-related quantification (e.g. for the HFE denoted *failure to perform feed and bleed cooling*) accounts already for premature terminations. To increase the efficiency of an EOC HRA in this respect, it would be therefore worthwhile to clarify first whether the EOO HFE quantification in the PSA accounts already for premature termination of manually initiated functions. Only if not, respective EOC HFEs need to be defined in connection with important EOO HFEs (say RAW>10) according to modeling proposal shown in Fig. 2-7.

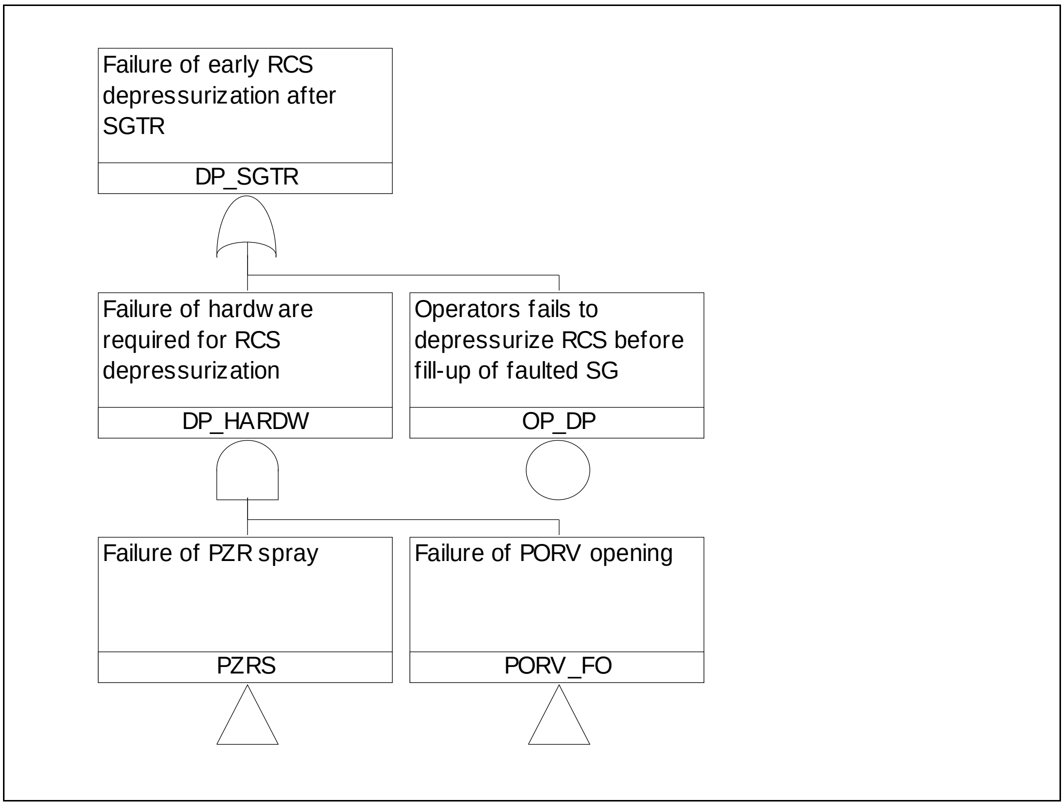

Fig. 2-6. One EOO HFE modeled in connection with two redundant hardware functions (simplified excerpt from a typical PSA model)

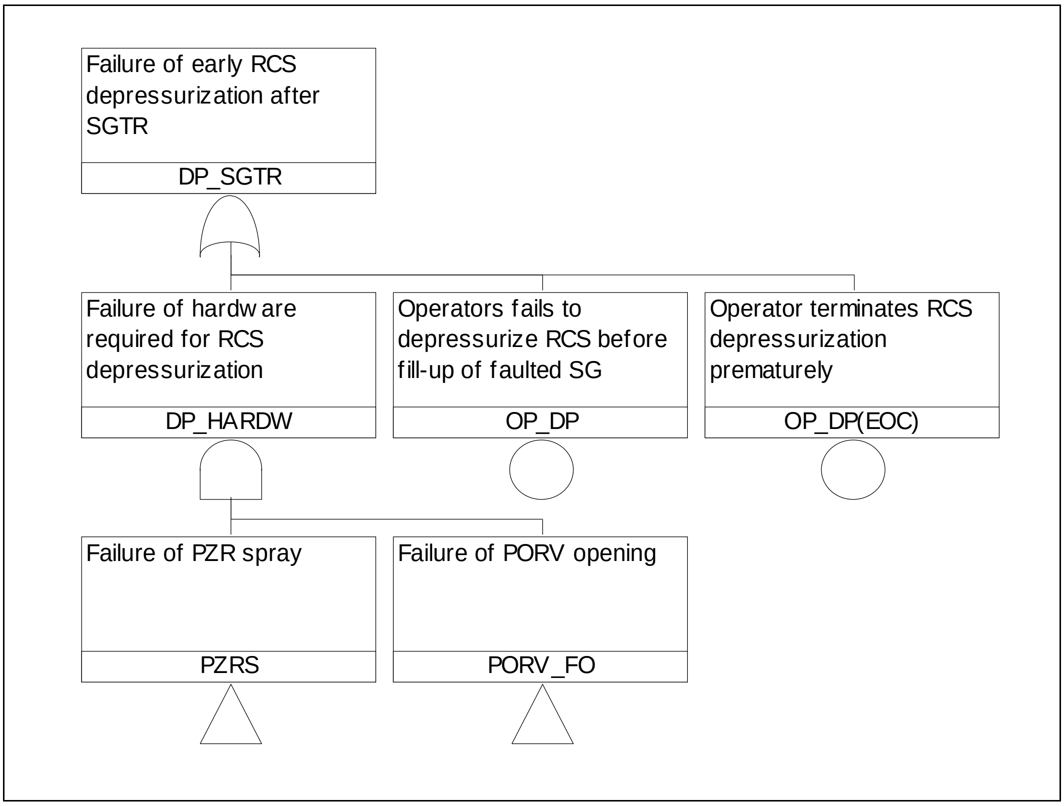

Fig. 2-7. EOO HFE modeling completed by a functionally related EOC HFE

Note basic event *OP_DP(EOC)* would be dispensable, given that the quantification model of basic event *OP_DP* accounts already for premature termination of RCS depressurization.

3. HFE analysis and quantification

3.1. 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 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 3-1 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) (Swain, 1987), *Human Error Assessment and Reduction Technique* (HEART) (Williams, 1988), and *Technique for Human Error Rate Prediction* (THERP) (Swain, Guttmann, 1983). 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.

3.2. Second generation HRA

The problem with the 'single-context-based' quantification in first generation HRA is that it is rather uncertain whether a so-obtained HEP covers as well adverse deviations (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 (NUREG-1624, 2000), MERMOS (Le Bot et al., 1997, 1999; Bieder et al., 1998; Le Bot, 1999, 2000), and MDTA (Kim et al., 2005, 2006a, 2006c). These methods are presented in Sections 3.2.1 to 3.2.3. In addition, the GRS method (Fassmann, Preischl, 2003) is presented in Section 3.2.4, since it addresses adverse combinations of performance conditions and cognitive factors. CREAM (Hollnagel, 1998) is reviewed in Section 3.2.5, 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 3.2.6.

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 an area of undergoing research, especially in the field of decision error quantification. An analyst is not in the position to choose between 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 3.2.1 to 3.2.5 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 3-1. EOC quantification with first generation HRA methods

EOC (HFE)	Context (system, scenario)	EOC prob.	Quantification details (excerpt)	Source (Table 2-2)
1.1. Premature switchover to sump recirculation	Contribution to failure of low pressure injection (LPI) after LOCA	10^{-2}	Screening value based on ASEP	(d)
1.2. Termination of SI	Contribution to failure of early inventory makeup after LOCA	$5.4x10^{-5}$	HEP (based on simulator exercise data) for procedure application, combined with HEPs (mainly based on THERP) for correction options from additional indications and personnel	(e)
1.3. Isolation of SG relief valve	Contribution to continuous leak through ruptured SG	$2x10^{-1}$	HEP from simulator exercises statistic; potential for stereotype response slip	(e)
1.4. Termination of bleed and feed operation (PORV closing or SI stop)	Scenario with loss of FW, and manual start of feed and bleed cooling	$2x10^{-2}$	HEART; basic HEP of $3x10^{-3}$, upward adjustment due to *unfamiliarity* and *objectives conflict*; no recovery routes modeled	(g)
1.5. Primary circuit dilution	Situation when high capacity makeup pump has to be in operation during startup dilution and all RCPs stop	$4x10^{-1}$	Special model for quantifying erroneous actions after correct diagnosis (Vaurio, Vuorio, 1991); HEP of $4x10^{-1}$ driven by: *no EOP,* and *stress*	(f)
1.6. Termination of SI	Contribution to failure of early inventory makeup after LOCA	$6.4x10^{-5}$	THERP; HEPs for procedure application under stress, combined with HEPs for correction options from additional indications and personnel	(b)
1.7. FW back-throttling or stop of special and emergency FW pumps & restart inhibition (*)	Scenarios with degraded secondary CCW	$6.2x10^{-4}$	As for EOC 1.6; EOC 1.7 driven by: misleading indication due to adverse scenario evolution (AFW fails with delay), potential for stereotype response slip	(b)
1.8. Start of a RCP	Contribution to seal LOCA in scenarios with degraded primary CCW	$1.2x10^{-2}$	As for EOC 1.6; EOC 1.8 driven by: misleading potential in EOP and conflicting goal (prevent steam bubble)	(b)
1.9. Isolation of RCP cooling water supply (from RWST)	Contribution to seal LOCA in loss of AC power scenario	$1.1x10^{-3}$	As for EOC 1.6	(b)

(*) This HFE comprises the following EOCs listed in Table 2-3: 2, 6, 18.

3.2.1 ATHEANA

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* (NUREG-1624, 2000, 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* (NUREG-1624, 2000, Table 5.6). 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 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 3-2. 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.

Comments. ATHEANA represents a milestone in the field of HRA method development. The concept of EFCs - which was introduced already in 1996 (Cooper et al., 1996) - is essential for providing HEP estimates based on realistic causes, and provided directive input for the research on second generation HRA. Nevertheless, predictive EFC identification and modeling must be seen as a rather novel and challenging HRA task (c.f. Dougherty, 1993). 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 3-2 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 (NUREG-1842, 2006, 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 or UAs worth concern* (NUREG-1624, 2000, 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 3-2, *back-throttling or shutdown of secondary cooling flow in a loss of main feedwater (MFW) scenario*): overcooling concern in combination with multiple failures of SG level instrumentation. An unfair reviewer may call in question the high effort (dozens of pages of documentation) required to come up with this finding, which appears as obvious in advance. However, this viewpoint would reflect a misinterpretation of the ATHEANA HRA for EOC 2.1. An appropriate interpretation would be that one EFC retained as worth for quantification after a systematic EFC search and a thorough evaluation of the identified EFCs. In view of this interpretation however, the ATHEANA HRA result for EOC 2.1 becomes very sensitive. The retained EFC has a probability of 10^{-7}. Thus the assumption of the adequacy 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; c.f. the total loss of feedwater events in Trojan (1983) (Forester et al., 1997) and Davis Besse (1985) (NUREG-1154, 1985). The implication is that second generation HRA should aim at a broader modeling of contexts (instead of focusing single EFCs).

In spite of their incompleteness regarding context modeling, 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 3-1, HEART, EOC probability of 0.02) and EOC 2.5 (Table 3-2, 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.

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* (NUREG-1624, 2000, 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 (Forester et al., 2004).

Table 3-2. Examples of post-initiator EOC quantification with the ATHEANA method

EOC (HFE); Scenario (*1)	EFC, given scenario	EFC prob.	HEP, given EFC	EOC prob. (*3)
2.1. Back-throttling or shutdown of secondary cooling flow; Loss of MFW	Overcooling concerns (10^{-1}), and Failure of multiple SG level indicators in the first 30 min (10^{-6})	10^{-7}	$5x10^{-1}$	$5x10^{-8}$
2.2. Interruption of early makeup of primary inventory (SI termination); SLOCA (*2)				
2.2.1. SLOCA due to pipe/vessel rupture (base case)	Rupture of PZR or surge line is the cause of the LOCA	10^{-1}	10^{-1}	10^{-2}
2.2.2. SLOCA 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} to 10^{-3}	10^{-1}	10^{-5} to 10^{-4}
2.2.3. SLOCA through stuck-open PZR safety valve (deviating case)	N/A (this LOCA variant is assumed as certainly error-forcing)	1	10^{-1}	10^{-1}
2.3. Termination of AFW during forced secondary cooling operation; SGTR	4-out-of-4 failure of narrow range (NR) SG water level gauge	$1.67x10^{-5}$	$5x10^{-1}$	$8.35x10^{-6}$
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	$1.6x10^{-3}$	$5x10^{-1}$	$8x10^{-4}$
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	$8.79x10^{-2}$	$5x10^{-1}$	$4.4x10^{-2}$

(*1) The HRAs of EOCs 2.1 and 2.2 are from source (i) in Table 2-2 and the HRAs of EOCs 2.3 to 2.5 from source (j).

(*2) 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.

(*3) 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 $4x10^{-2}$ for EOC 2.1 and 10^{-1} for EOCs 2.3 to 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 meaning the recovery failure would be dominated by contributions from LPI hardware failures.

3.2.2 MERMOS

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.[5] According to the terminology outlined in Section 1.1, a

[5] The MERMOS guidance does not comprise details on the identification of human factor missions. The missions are determined from a functional analysis of the plant after an IE (Le Bot et al., 1999, p. 856).

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 (Le Bot, 2000, p. 78). Table 3-3 illustrates the concept of context modeling for this EOC-related mission failure. Multiple failure scenarios are considered and explicitly modeled. Each failure scenario represents a path that leads to the mission failure (Le Bot, 2000, p. 77; Le Bot et al., 1999, p. 854). 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 (Let Bot, 2000, 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 $3x10^{-5}$ to $3x10^{-4}$, which is supposed to cover failure scenarios *that cannot even be imagined*:

$$p_F \approx p_r + (p_{11} \; x \; p_{12} \; x \; \ldots) + (p_{21} \; x \; p_{22} \; x \; \ldots) + \ldots \qquad \text{Eq. 3-1}$$

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 (Let Bot et al., 1999, p. 854-857).

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 ($3x10^{-5}$ to $3x10^{-4}$) 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. (2005, p. 61), or 10^{-5} to 10^{-4} by Kirwan (1994, 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 3-3, for instance, are insufficiently explained in the reference (Le Bot, 2000) 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 (Le Bot, 2000, p. 82). As it can be seen in Table 3-3 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.

Table 3-3. 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 (Le Bot, 2000)

	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.

3.2.3 The MDTA method

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 (e.g. end state *ESDE* or *GTRN* in Fig. 2-4); (b) unsafe action (UA, i.e. EOC or EOO), given diagnosis failure; (c) non-recovery, given UA.

Table 3-4 presents an example about their quantification. Fig. 3-1 illustrates the integration of the EOC quantification results into a SLOCA event tree. 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 the misdiagnosis tree shown in Fig. 2-4) is assigned to the diagnosis of an excessive steam demand event (instead of a SLOCA). 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 3-5 presents the dominant path contributing to the erroneous ESDE diagnosis probability of 6.44×10^{-3}.

Misdiagnosis quantification is structured by the three contributors (PD, OE, IF) defined in Section 2.2.3.

(i) 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 subgroups, and it is determined which fraction of them would force a decision contributing to misdiagnosis. In the misdiagnosis path presented in

Table 3-5 for instance (SLOCA IE), the EOP analysis identified conditions with *adequate 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 inch).

(ii) Table 3-6 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 $1.6x10^{-2}$ to $3x10^{-4}$, were derived from both expert judgment and the *Caused-Based Decision Tree* (CBDT) method; (Grobbelaar, Julius, 2003) is indicated as the CBDT reference. 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 Fig. 2-4), and thus a basic HEP of 0.006 (Table 3-6) is used to quantify misinterpretation in the path presented in Table 3-5. Error correction is not credited, since the STA's checking does not address containment pressure.

(iii) The *instrumentation failure* (IF) contributions are 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 IF for the containment pressure indication. The test interval is 18 months. A beta factor of 0.1 is used to quantify multiple channel failures, yielding the failure probability of 0.0002 assigned to the respective IF limb in Fig. 2-4.

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 x 0.1) in the best case. Table 3-7 summarizes these recovery HEPs, which are adapted from the CBDT method.

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) plant dynamics (PD) and instrumentation failure (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 (Reer et al., 2004, Table 7). 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* (NUREG-1624, 2000, Table 15a). However, the associated shortcoming is diminished, since the MDTA method additionally accounts for an operator error (OE) in information gathering or rule interpretation (OE limbs in Fig. 2-4).

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; c.f. the CBDT summary in (Moieni et al., 1994). Thus the MDTA quantification can be denoted as THERP-based (or judgment-based) with the contributions from two EFC types (PD, IF) on top of it. In the HRA example (Table 3-4), the ESDE diagnosis probability would drop from 6.44E-3 to 2.68E-4 if OE contributors (in the sense of the OE limbs in Fig. 2-4) 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 Reer et al., 2004, Table 12).
- In the MDTA method, this kind of dependency issue is not addressed. As it can be seen in Fig. 2-4, the operator errors in interpreting the rules related to 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.

For the quantification of post-EOC (or post-UA) recovery, the MDTA method and THERP adaptation in the Swiss EOC pilot study (Reer et al., 2004) apply the (by-and-large) same set of factors, namely: time available for recovery, and procedural guidance on recovery. 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 (Reer et al., 2004), 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.
- Moreover, the pilot study credits as well recovery in case of time windows (TWs) below 0.5 h. Note the MDTA guidance suggest a *TW>0.5 h* criterion for the inclusion recovery. Operational events indicate however a notable portion of EOCs recovered within 30 min (Reer, 2002).

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.

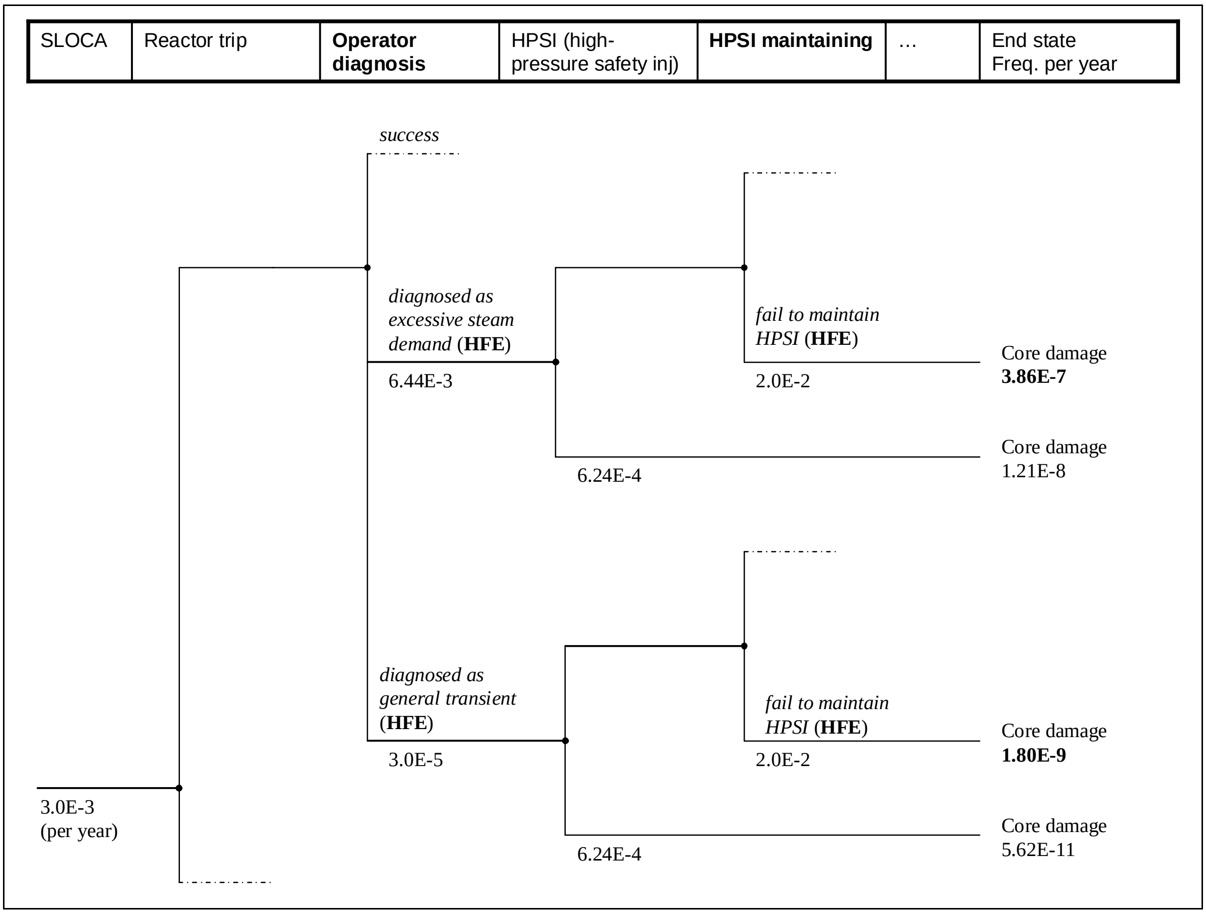

Fig. 3-1. Excerpts from a SLOCA event tree with EOC HFEs integrated
Source: Kim et al., 2006c. Acronyms spelled out for clarity.

Table 3-4. MDTA method results of the quantification of premature HPSI termination identified as an unsafe action (UA) in a SLOCA scenario (Kim et al., 2006c)

Misdiagnosis	Misdiagnosis probability *(analysis excepts in Fig. 2-4)*	Probability of UA, given misdiagnosis *(rules in Section 2.2.3)*	Probability of non-recovery		Total (product)
			procedural guidance on recovery	STA's independent checking of CSF	
General transient event (GTRN)	$3.0x10^{-5}$	1	$2.0x10^{-1}$	$1.0x10^{-1}$	$6.0x10^{-7}$
Excessive steam demand event (ESDE)	$6.44x10^{-3}$ *(dominant path in Table 3-5)*	1	$2.0x10^{-1}$	$1.0x10^{-1}$	$1.29x10^{-4}$

Table 3-5. MDTA quantification of a path leading to an erroneous diagnosis of ESDE (Table 3-4) in a SLOCA scenario (Kim et al., 2006c)

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 inch out of all SLOCA cases (leak sizes from 0.38 to 1.91 inch).
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 3-6, case "NOT & (AND or OR)". Error correction by STA not credited because CSF procedure does not cover containment pressure checking.
OVERALL		0.004	

Table 3-6. Basic HEPs for OE quantification in the MDTA method (Kim et al., 2006c)

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

Table 3-7. Recovery quantification in the MDTA method (Kim et al., 2006c)

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

3.2.4 The GRS method

Method summary. To quantify a potential EOC identified (Fig. 2-3), the GRS method (Fassmann, Preischl, 2003) addresses cognitive factors and ergonomic factors interacting with human cognition. Table 3-8 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. Swain, Guttmann, 1983). 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 3-9. 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 3-9 are meant to be used in a screening analysis. Detailed quantification using expert judgment is recommended, given that an EOC quantified with a screening probability shows an essential contribution to the PSA result. A special kind of judgment process with shift and training personnel involved is recommended: the judgment is decomposed into stages, and the experts are asked to choose probability intervals (Fassmann, Preischl, 2003, p. 179).

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 3-8, 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 Mosneron-Dupin et al. (1997).

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 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 3-8) factor-by-factor, would work. Some of the factors (e.g. *operator may have difficulties in recognizing processes changing with time* - fourth factor in group D) 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 (Reer, 1999).

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' (c.f. Reer, 2004a) 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 proposed need of an extensive judgment process (involving plant personnel) to address the EOCs identified as important after screening may be debatable. Extensive work informed by plant-specific details is already required for the assessment of the cognitive and ergonomic factors. The assessment results appear to be sufficient for the derivation of a HEP. The benefit of an additional, extensive judgment process appears to be questionable.

Table 3-8. Excerpts from the assessment guidance on cognitive factors in the GRS EOC HRA method (translated from: Fassmann, Preischl, 2003, Table 6.2)

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 consequence.	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

Table 3-9. EOC probabilities (mean values for screening) proposed in the GRS method for five performance load levels

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

Compiled and translated from: Fassmann, Preischl, 2003, Ch. 8.

3.2.5 CREAM

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 $5x10^{-6}<p<10^{-2}$ to the 'best' mode labeled *strategic*. The basis for these intervals is described as *commonly accepted estimates in the available HRA literature* (Hollnagel, 1998, 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 $5x10^{-4}$ 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, mainly: Beare at al. (1984); Gertman, Blackman (1994); Swain, Guttmann (1983); Williams (1989). 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 (Hollnagel, 1998, p. 234-254).

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 (ASME, 2002; NUREG-1792, 2005).

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.

With some adaptation however, CREAM appears to be applicable to an EOC HFE. Given the need to quantify premature SI termination for instance, the task to be addressed by CREAM may be defined as *maintain SI operation*, and decomposition and failure mode assignment should be carried out accordingly. In any case however, CREAM does not present guidance for the identification EOCs on the level of HFEs.

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 (Kim et al., 2006b). 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* (Hollnagel, 1998, 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 3-10[6] 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 is 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 (Hollnagel, 1998, p. 252). It is not however clear what are the directions to follow in order to

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[6] Note in a basis analysis these levels would yield *$0.001<p<0.1$*, i.e. the failure probability interval for a *tactical control mode*.

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.

Table 3-10. Levels of common performance conditions (CPCs) resulting in no modification of the basic HEP for an interpretation failure in an extended CREAM analysis (Hollnagel, 1998, 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

Note possible basic HEPs for interpretation failures are: 0.2 for *faulty diagnosis*; 0.01 for *decision error*; 0.01 for *delayed interpretation* (Hollnagel, 1998, p. 252).

3.2.6 Other approaches

Finally, it is worth mentioning that various approaches exist to better utilize empirical data for the derivation of context-specific HEPs (Sträter, Bubb, 1999; Sträter, 2005; Gertman et al., 2001; Hallbert et al., 2004; Kirwan et al., 2004; Reer, 2004a; Reer, Dang, 2006a; Reer, Dang, 2006b). 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 does not address EOCs; it is announced that a prototypical approach to EOC quantification has been developed (Kirwan et al., 2004).

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 (Kirwan et al., 2004).

3.3. Qualitative quantification results: contributing factors

All the quantification cases referred to in Sections 3.1 and 3.2 (except the screening value assignment for EOC 1.1 in Table 3-1) were qualitatively evaluated. For clarity, these cases are compiled in Table 3-11. Note they do not cover the full range of EOC identification results listed in Table 2-3; see notes (*2) and (*4) in this table.

Table 3-12 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 3-5) - 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 3-3. As presented in the method summary (Section 3.2.2), 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 3-3 (MERMOS HRA). Therefore, no factor was assigned to it.

Table 3-11. EOC quantification cases

EOC	Source (Table 2-2)	Quantification method	Quantification details in:
Termination or throttling of SI	(b)	THERP	Table 3-1
	(e)	misc.	Table 3-1
	(h)	MERMOS	Table 3-3
	(i)	ATHEANA	Table 3-2
	(k)	MDTA	Table 3-4
Back-throttling or shutdown of secondary cooling flow	(b)	THERP	Table 3-1
	(i)	ATHEANA	Table 3-2
Termination of AFW	(j)	ATHEANA	Table 3-2
Stop of special and emergency feedwater	(b)	THERP	Table 3-1
Isolation of SG relief valve	(e)	misc.	Table 3-1
Isolation of RCP cooling water supply (from RWST)	(b)	THERP	Table 3-1
PORV closing or SI stop (termination of bleed and feed in loss of FW scenarios)	(g)	HEART	Table 3-1
	(j)	ATHEANA	Table 3-2
PORV closing (termination of forced RCS cooling in SGTR scenarios)	(j)	ATHEANA	Table 3-2
Primary circuit dilution	(f)	misc.	Table 3-1
Start of a RCP	(b)	THERP	Table 3-1
Inhibition of EFW restart	(b)	THERP	Table 3-1

The assignments show that two or more factors are contributing to most of the quantification results; e.g. a *conflicting goal* and a *misleading EOP* are identified as contributing to the start of a RCP under inappropriate operating conditions (Table 3-1). 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. Note adaptations (based on expert judgment) of THERP were required for quantifying other, more specific factors like *conflicting goal*; c.f. (Reer et al., 2004).

Instrumentation failures contribute to most of the EOCs quantified in second generation HRA (ATHEANA, MDTA). Factors common to both (first and second generation HRA) are: misleading indication due to adverse scenario evolution or IE variants (e.g. addressed in MDTA under the heading of *plant dynamics*), conflicting goal, and random errors.

Table 3-12. Contributing factors identified from various cases (Table 3-11) of EOC quantification

Contributing factor	EOC (Source, Method)	
	1st generation methods	2nd generation methods
<u>Factors relevant for to specific causes of decision errors</u>		
Conflicting goal or Anticipation of further operation objective	PORV closing or SI stop (termination of bleed and feed in loss of FW scenarios) (g, HEART) Start of a RCP (b, THERP)	Back-throttling or shutdown of secondary cooling flow (i, ATHEANA) Termination or throttling of SI (h, MERMOS)
Misleading indication due to adverse scenario evolution or IE variant	Stop of special and emergency FW (b, THERP)	Termination or throttling of SI (i, ATHEANA; k, MDTA)
Misleading indication due to instrumentation failure	-	Back-throttling or shutdown of secondary cooling flow (i, ATHEANA) PORV closing (termination of forced RCS cooling in SGTR scenarios) (j, ATHEANA) PORV closing or SI stop (termination of bleed and feed in loss of FW scenarios) (j, ATHEANA) Termination of AFW (j, ATHEANA) Termination or throttling of SI (k, MDTA; i, ATHEANA) (*1)
Procedure unavailable or misleading	Primary circuit dilution (f, misc.) Start of a RCP (b, THERP)	Termination or throttling of SI (k, MDTA) (*2)
Stress	Primary circuit dilution (f, misc.) And all cases (Table 3-11) quantified in source (b)	-
Unfamiliarity	PORV closing or SI stop (termination of bleed and feed in loss of FW scenarios) (g, HEART)	-
<u>Misc. factors</u>		
Potential for a stereotype response slip	Inhibition of EFW restart (b, THERP) Isolation of SG relief valve (e, misc.)	-
Random error in procedure application (rule interpretation, information gathering, display reading)	Termination or throttling of SI (e, misc.) And all cases (Table 3-11) quantified in source (b)	Termination or throttling of SI (h, MERMOS; k, MDTA)

(*1) The IF contribution to this EOC is small; see Fig. 2-4, and Table 3-2 (sub case 2.2.2), respectively.

(*2) CSF procedure does not cover containment pressure checking (see Table 3-5).

The contributing factors relevant to specific decision error causes are, by-and-large, addressed by the set of factors accounted for in PSI's development of a new quantification method (Reer, Dang, 2006b). The relations are coarsely presented in Table 3-13. Note the concept in (Reer, Dang, 2006b) proposes a context-specific assessment of relevant factors in two stages. For instance, factor VD (verification difficulty) is evaluated in the context of a specific condition leading to an initial motivation of an inappropriate action, and the evaluation is supposed to account for factors like *EOP availability*, *EOP clarity* and *familiarity*.

Of course, a missing relation in Table 3-13 does not mean that the factor addressed in (Reer, Dang, 2006b) is fundamentally novel. It just means that the factor was not explicitly identified as a HEP contributor in any of the quantification cases presented in Table 3-11. Neglecting nuances in wording, all of the factors addressed in (Reer, Dang, 2006b) are as well covered by the descriptions of existing HRA methods. By-and-large for instance, the factor denoted as *distracted from monitoring* in the ATHEANA method relates to *adverse distraction*.

Table 3-13. Coarse relations between HEP contributing factors from various sources

Factors in (Reer, Dang, 2006b)	Related factors (see Table 3-12) in EOC quantification cases (Table 3-11)
<u>Factors inducing initial motivations or considerations of inappropriate actions</u>	
Misleading indication or instruction	Procedure unavailable or misleading Misleading indication due to adverse scenario evolution or IE variant Misleading indication due to instrumentation failure
Adverse exception (from boundary conditions of usually appropriate actions)	Misleading indication due to adverse scenario evolution or IE variant
Adverse distraction	-
Risky incentive	Conflicting goal or Anticipation of further operation objective
<u>Factors mediating the impact on the EOC likelihood</u>	
Verification hint	Procedure unavailable or misleading Stress
Verification means	Procedure unavailable or misleading
Verification difficulty (cognitive)	Procedure unavailable or misleading Stress Unfamiliarity
Verification effort (physical)	-
Time pressure	Stress
Benefit prospect	Conflicting goal or Anticipation of further operation objective
Damage potential (aversion)	-
Personal redundancy	-

3.4. *Summary and recommendations*

3.4.1 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 3-14 provides a high-level summary of their features.

Table 3-14. 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. In: NUREG-1624 (2000, App. B and C); Fukuda et al. (2000).	• Expert judgment of the method user
MERMOS	Multiple contexts; emphasis on failure paths associated with so-called CICAs	Yes. In: Le Bot (2000); but very concise example; no discussion of probability assignments.	• Expert judgment of the method user
CREAM	Nominal context	Yes. In: Hollnagel (1998, Ch. 9); but no EOC HFE example.	• 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 reviews. • For HFEs retained after screening: Expert judgments of the method user and plant experts.
MDTA	Multiple contexts; limited to 3 types (PD, OE, IF); c.f. Fig. 2-4	Yes. In: Kim et al. (2005, 2006a, 2006c).	• 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).

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 3-12) indicate promising trends in explicitly addressing decision-related factors like *misleading indications* (ATHEANA, MDTA) or *conflicting goals* (ATHEANA, MERMOS).

PSA-relevant experience with second generation methods is rather limited (ATHEANA, CREAM, GRS, 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 the respect to the assignment of context-specific HEPs.

- There is strong reliance on direct numerical estimation of a HEP (ATHEANA, 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, 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 whether aspects related to human decision-making are adequately represented in the final HEP obtained.

3.4.2 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 3.2 have (or point to) advanced features, which in turn provide orientations for further development work. These advanced features are briefly outlined below.

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 (c.f. the introductory notes in Section 3.2).

b) Accounting for shortcomings in context identification and evaluation. This feature is an element of the methods MERMOS and MDTA. As commented in Section 3.2.1, 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 EFFs) - 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 3.2.1, a problem with the ATHEANA guidance for EFC identification 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, diagnosis*) or MDTA *(plant dynamics, instrumentation failure, 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 (Forester et al., 2004) and the recent outline of an EOC quantification method (Reer, Dang, 2006a; Reer, Dang, 2006b). 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 3-8).

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 (c.f. Reer, 2004a).

g) Using screening values for initial quantification. This feature is element of the GRS method and CREAM. It is viewed here as 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 3.2.6, is associated with future data analysis required to increase the credibility of quantitative EOC prediction and thus the acceptance of EOC HRAs.

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.

4. Summary and conclusions

In order to obtain insights for the preparation of a pilot study on a full-scope HRA of post-initiator errors of commission (EOCs) including both identification and quantification, a review has been carried out addressing: five emerging methods (ATHEANA, CREAM, GRS, MERMOS, MDTA, CESA), 19 EOCs predicted in PSA/HRA applications, and 17 EOC quantification cases.

4.1. EOC identification

Table 4-1 presents a high-level summary of the scope of the emerging methods according to the information published so far. Four of the emerging methods (ATHEANA, GRS, MDTA, CESA) provide as well guidance for EOC identification on the level of HFEs to be integrated in a PSA model. Three of them use a search scheme starting with a given scenario (ATHEANA, GRS, MDTA). The review of the provided guidance details concludes that these methods have shortcomings in scenario prioritization. Prioritization is viewed here as essential for the feasibility of EOC HRA because of the large number of scenarios associated with the safety of complex installations like NPPs. The CESA search scheme, which has been applied so far in a pilot study (Reer et al., 2004), proceeds from possible operator actions (known from procedures and related training) to the affected systems to scenarios. It provides a formalized way for scenario identification and prioritization. CESA's limitation, associated with the emphasis on the EOC potential of procedural actions, appears to be acceptable, since other methods (GRS, MDTA) propose as well procedural criteria for the inclusion of an EOC. Guidance to reduce this problem has been implemented so far in an updated description of the EOC identification part of the CESA method (Reer, Dang, 2007).

4.2. EOC quantification

With respect to EOC quantification, the review addressed ten HRA cases analyzed with first generation methods (e.g. THERP) and seven cases analyzed with second generation methods (ATHEANA, MDTA, MERMOS). In the context of the latter, an in-depth review of five second generation methods was carried out (ATHEANA, CREAM, GRS, MERMOS, 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, 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). Problematic issues are associated with the implementation of multiple context modeling (EFC search effort, reproducibility, 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, GRS) and the concept of reference cases of context-specific HEPs (ATHEANA outlook) provide promising orientations for achieving progress towards data-based EOC quantification.

4.3. Learning by doing: need to shift from conceptual to application-oriented development work

HRA research on EOCs is undergoing since more than 10 years (e.g. Cooper et al., 1996). Although much research on method development has been carried out, nowadays analysts are not in the position to choose between working EOC HRA methods, i.e. methods applicable under the constraints in industrial PSA and addressable in a regulatory review process. Much method development work with conceptual emphases has been carried 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 4-2.

Table 4-1. 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* (Cooper et al., 1996; NUREG-1624, 1998, 2000)	Yes	Yes
MERMOS: *Méthode d'Evaluation de la Réalisation des Missions Opérateur pour la Sûreté* (Le Bot et al., 1997, 1999; Bieder et al., 1998; Le Bot, 2000)	No (*1)	Yes
CREAM: *Cognitive Reliability and Error Analysis Method* (Hollnagel, 1998)	No (*2)	Yes
GRS: EOC HRA method developed by *Gesellschaft für Anlagen- und Reaktorsicherheit* (Fassmann, Preischl, 2003)	Yes	Yes
MDTA: *Misdiagnosis Tree Analysis* method (Kim et al., 2005, 2006a, 2006c)	Yes	Yes
CESA: *Commission Errors Search and Assessment* method (Dang et al., 2002; Reer et al., 2004; Reer, Dang, 2007)	Yes	No (*3)

(*1) The MERMOS HRA guidance does not address (in detail) the identification of *human factor missions*, but addresses the identification of so-called *failure scenarios* for a given mission. The missions are determined from a functional analysis - which is carried out by the PRA analyst (with help from the HRA analyst if necessary) - of the plant after an IE (Le Bot et al., 1999, p. 856).

(*2) CREAM presents guidance for the identification of *cognitive function failures* for a task assumed as known from PSA.

(*3) THERP values were used in the EOC pilot study (Reer et al., 2004). An outline of a method for alternate quantification is summarized in (Reer, Dang, 2006a); a publication on more details is under preparation.

Table 4-2. EOC HRA with respect to large-scale applications: status and outlook

Large-scale EOC identification No EOC quantification	Borssele EOC HRA, Dutch PSA, 2-loop 480 MWe PWR (Versteeg, 1998; Julius et al., 1995)
Large-scale EOC identification Small-scale EOC quantification with first generation method	EOC pilot study, Swiss reference PSA, PWR (Dang et al., 2002; Reer et al., 2004)
Large-scale EOC identification Small-scale EOC quantification with second generation method	Outstanding (short-term milestone)
Large-scale EOC identification Large-scale EOC quantification with second generation method	Outstanding (medium-term milestone)

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