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Applicability of HRA to Support Advanced MMI Design Review

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Abstract

More than half of all incidents in large complex technological systems, particularly in nuclear power or aviation industries, were attributable in some way to human erroneous actions. These incidents were largely due to the human engineering deficiencies of man-machine interface (MMI). In nuclear industry, advanced computer-based MMI designs are emerging as part of new reactor designs. The impact of advanced MMI technology on the operator performance, and as a result, on plant safety should be thoroughly evaluated before such technology is actually adopted in nuclear power plants. This paper discusses the applicability of human reliability analysis (HRA) to support the design review process. Both the first-generation and the second-generation HRA methods are considered focusing on a couple of promising HRA methods, i.e., ATHEANA and CREAM, with the potential to assist the design review process.

Key Words : man-machine interface, human reliability analysis, advanced control room, advanced MMI, MMI validation, CREAM, ATHEANA

1. Introduction

Needless to mention the TMI-2 or other major incidents, the importance of man-machine interface (MMI), or sometimes called human-machine or human-system interface, to reliable human performance and nuclear safety is widely recognized [1, 2]. Advanced, computer-based MMI designs are emerging as part of new reactor designs, like Korean Next Generation Reactor (KNGR).

Advanced control room and man-machine interface are developed primarily with advanced instrumentation and controls (I&C) based on digital technology, and a variety of operator aid systems based on modern computer technology, e.g., computerized alarm system or large display panel. Hence, considerable change is expected in the degree of plant automation, in the ways in which the operators interact with the plant, and as a result, in the overall role of plant operators. All these aspects of potential change may have significant implications for plant safety, e.g., inappropriate termination of coolant injection due

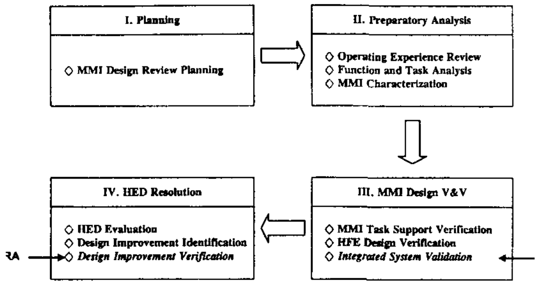

Fig. 1. The Role of HRA in a Generic MMI Design Review

to loss of situation awareness.

Therefore, the safety impact or risk implications of advanced MMI technology in terms of operator performance or potential human errors should be thoroughly evaluated before such a technology is actually adopted in nuclear power plants. The human reliability and erroneous actions have been investigated in the discipline of human reliability analysis (HRA) as either a design tool or part of probabilistic safety analysis (PSA) [3]. Hence, HRA can be used as an evaluation tool to identify vulnerabilities to human error or human engineering deficiencies of the advanced MMI.

The objective of this paper is three-fold:

1) To discuss the role of HRA in terms of the US NRC' s general framework for MMI design review;
2) To characterize the salient features of available HRA techniques, so called the first-generation and the second-generation HRAs, from the perspective of their application to support the advanced MMI design review process; and
3) To provide our insights as regards the applicability of the promising HRA methods to the design review process.

2. Generic MMI Design Review Process

A generic MMI design review process that can be applied to either conventional or advanced MMI has been developed by the US NRC [4]. As shown in Figure 1, the generic review process consists of the following four phases:

I. Planning,
II. Preparatory Analysis,
III. MMI Design Verification and Validation (V&V), and
IV. Resolution of Human Engineering Discrepancies (HEDs).

Firstly, an MMI design review is planned. Next, a preparatory analysis is carried out, which includes a review of relevant operating experience, an analysis of system functions and personnel functions and tasks, as well as a characterization of existing or planned MMI systems.

Once the planning and preparatory analyses are completed, then the important tasks to verify and validate the MMI design and resolve identified HEDs can be carried out. The focus of the generic MMI design review process is on these last two phases.

The MMI design V&V of the third phase aims to identify any HEDs that may exist in the MMI. The HEDs can be identified by following the steps below:

1) MMI Task Support Verification: HEDs are identified for personnel task requirements that are not fully supported by the MMI, and for MMI elements which are not needed to support a personnel task requirement or distract from task performance.
2) Human Factors Engineering (HFE) Design Verification: HEDs are identified if the MMI design or implementation is inconsistent with the HFE guidelines.
3) Integrated System Validation: After the HEDs identified in the previous steps are resolved, HEDs may be further identified by a performance-based evaluation of the integrated

MMI design to ensure that it supports safe plant operation.

In the first two steps of the third phase indicated above, the HEDs of the MMI can be rather easily identified because, among others, the MMI review in these steps does not properly address the internal aspects of the human operator. It is the last step, i.e., integrated MMI system validation, for which HRA can be usefully applied to identify further HEDs that may still exist in the MMI.

The HEDs can be identified by performing an HRA for the MMI because the HRA helps to find error-likely context or error-prone situations resulting from some deficiencies of the MMI. The more advanced technology does the MMI incorporate, the more likely are the human erroneous actions to be caused by cognitive errors in general, because a shift of the operator' s role toward pure supervision of the process or operational aspects.

Without the aid of HRA, the integrated system validation should be performed using only a simulator or other suitable representation of the MMI to determine the adequacy of MMI to support personnel performance in maintaining plant safety. However, with an HRA, the MMI can be validated in an integrated fashion more easily and thoroughly than otherwise possible.

By going through the following three steps of the last phase the HEDs of the MMI design identified above are resolved to result in an improved design: 1) HED evaluation, 2) design improvement identification, 3) design improvement verification.

Once the HEDs are identified in the third phase, their importance to safety, and plant or personnel performance is assessed. The important HEDs are then used to identify potential design improvements to the MMI. The design improvements are implemented, and then, verified to ensure that they meet all design specifications [5]. Furthermore, one should verify that the static and dynamic characteristics of the improved design are acceptably integrated with the rest of the MMI. HRA also can assist the final step of design improvement verification by ensuring that no error-prone situations will occur in the improved MMI under perceivable conditions.

3. The First-Generation HRA Methods

Thus far a number of HRA methods have been proposed and applied to various situations where humans are involved. These HRA methods may be classified as either the first or the second generation [6-8]. The typical characteristics of the first-generation HRA are presented below. Hence, any HRA method that has most of these characteristics can be classified as belonging to the first generation. In the present and the following sections, we discuss the first- and the second-generation HRA methods, respectively, in particular from the perspective of their application to advanced MMI design review.

The first-generation HRA methods were highly influenced by the PSA approach to an integrated assessment of plant risk. The most common and notable characteristics of the first-generation HRA methods can be summarized as follows:

1) Human Reliability Similarly Describable as Hardware Reliability: The first-generation HRA methods, typified by the technique for human error rate prediction (THERP) [9], are similar to those employed in conventional reliability analysis, except that human task activities are substituted for equipment outputs [8]. The THERP approach uses conventional reliability technology modified to account for greater variability and interdependence of human performance as compared with that of equipment performance. The assumption that human reliability can be similarly described as

equipment reliability is no more applicable, especially in the cognitively demanding task environment of the advanced, computer-based MMI.

2) PSA-cum-HRA: The first-generation HRAs were typically performed within the envelope of PSA, i.e., PSA-cum-HRA. Hence, the HRA is limited to consider the human actions that are included in the PSA event trees, and as a result, the quality of the analysis depends on the completeness and accuracy of the PSA modeling [8].

3) Binary Representation of Human Action: In PSA hardware equipment is represented as either succeeding or failing to perform the required function. Similarly, in the first-generation HRAs human action has been represented as either a success or a failure to carry out a given task. THERP' s human event tree is a typical example of this binary representation of human actions.

4) Dichotomy of Omission and Commission Errors: Since PSA is performed by describing the ways equipment respond or not respond to a challenge, the first-generation HRAs also have been directed at describing the variety of incorrectly performed actions, commonly referred to "human errors". As E. Hollnagel has indicated in reference 8, a tradition was soon established to distinguish between the failure to perform an action known as an "omission", and an unintended or unplanned action known as a "commission".

5) Focus on Phenomenological Aspects of Human Action: The first-generation HRA approaches put emphasis on the phenomenological aspects of human action because the dichotomy of errors of omission and commission refers to something that can be easily observed. That is, a person could either do something correctly, do it incorrectly (i.e., commission), or not do it at all (i.e, omission).

6) Little Concern of Cognitive Aspects of Human Actions: Human actions, erroneous or otherwise, are all to some extent cognitive. Therefore, human actions cannot be properly understood or analyzed without referring to the characteristics of human cognition. Cognitive error can be the cause of an omission as well as of a commission. Internal, cognitive aspects of human actions have not received due attention from the first-generation HRA approaches.

7) Emphasis on Quantification: In the first-generation HRAs, emphasis was placed on quantifying the probabilities of incorrect performance of human actions, i.e., human errors, identified in the PSA event trees. These quantification attempts have created a need for data on human error probabilities (HEPs) for the types of data considered in the first-generation HRAs. Example data types in this regard are i) an omission error of omitting an item of instruction when a written procedure is used, ii) a commission error of incorrectly reading quantitative information from an analog meter, and iii) a commission error of selecting wrong circuit breaker in a group of circuit breakers. The need for these data are quite artificial and may be an artefact of the PSA sequence model to some extent [8]. Some of these data may be effectively used only for those situations where the human actions can be relatively easily described along with quite simple task environment, such as a maintenance or test-related action. However, for the situations where human actions should be carried out in a more complicated task environment such as the main control room during a major plant upset, the application of such data may be neither feasible nor practically effective.

8) Indirect Treatment of Context: In the PSA-cum-

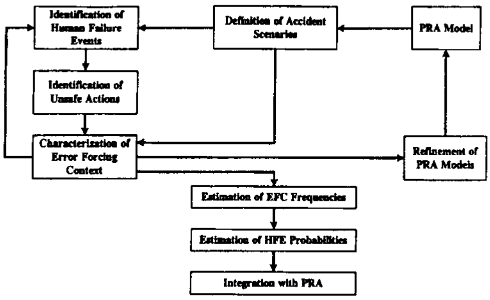

Fig. 2. ATHEANA HRA Method

HRA, human actions that need to be analyzed are identified from the PSA event trees. The task of interest is then decomposed into subtasks for which the data discussed above are applied as "nominal human error probabilities". The task analysis is complemented by the use of "performance shaping factors (PSFs)" that mean any factors influencing human performance. However, the way in which PSFs exert their effect on performance is not described by the operator model; instead, the influence of PSFs, i.e., context, on the operator performance is simply taken into account by multiplying the nominal HEPs with a weighted sum of the PSFs as follows:

$$\Pr(\text{HEP} \mid \text{Context}) = \Pr(\text{Basic HEP}) \times [\sum_i \text{PSF}_i \times \text{W}_i]$$

where W_i refers to a weighting factor of the i-th PSF for the specific task.

4. The Second-Generation HRA Methods

This section discusses the salient features of the second-generation HRA methods especially from the perspective of their application to advanced MMI design evaluation. Focus herein is placed on a couple of representative HRA methods, ATHEANA (A Technique for Human Error ANAlysis) and CREAM (Cognitive Reliability and Error Analysis Method), that have been recently developed by a series of USNRC-sponsored research and by E. Hollnagel, respectively.

Figure 2 shows a graphical description of the method used by ATHEANA [10, 11]. The method begins with human failure events (HFEs) that are identified from the accident scenarios of PSA model. The HFEs are then further characterized by unsafe actions (UAs), which mean those actions inappropriately taken, or not taken when needed, by plant personnel that result in a degraded plant safety condition. The next step is to characterize error-forcing context (EFC) that is the combined effect of performance shaping factors (PSFs) and plant conditions that create a situation in which human error is likely.

The following equation represents the way by which the HFE is quantified in ATHEANA:

$$P(\text{HEF}_{ijr}) = P(\text{EFC}_i) \times P(\text{UA}_j \mid \text{EFC}_j) P(\bar{R} \mid \text{EFC}_i \mid \text{UA}_j \mid E_{ij})$$

where

$P(\text{HEF}_{ijr})$: the probability of human failure event (HEF_{ijr}) occurring

$P(\text{EFC}_i)$: the probability of error-forcing context

$P(\bar{R} \mid \text{EFC}_i \mid \text{UA}_j \mid E_{ij})$: the probability of unsafe action in the EFC

$P(\bar{R} \mid \text{EFC} \mid \text{UA(E)}$: the non-recovery probability in the EFC and given the occurrence of the unsafe action and the existence of additional evidence (E_{ij}) following the unsafe action

Especially in view of its application to MMI design review, we can find that ATHEANA has the following characteristics:

1) ATHEANA has special merits for MMI evaluation like focusing on the identification of error-forcing context or error-prone situations. It also allows identifying likely human errors, in particular commission errors, that may occur in the error-forcing context following an accident,

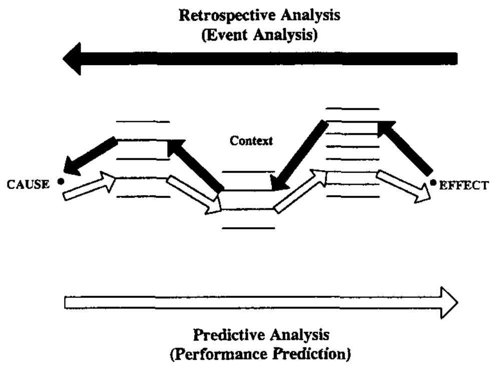

Fig. 3. Two Types of CREAM Anlaysis

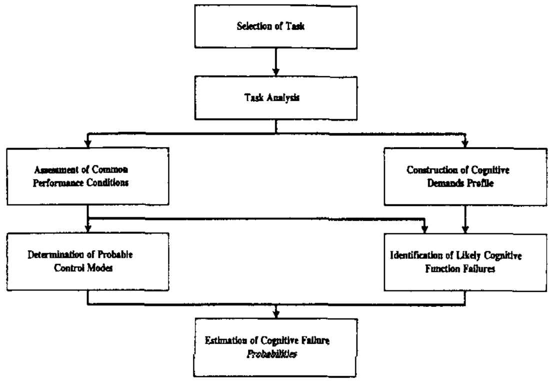

Fig. 4. Human Performance Prediction in CREAM HRA Method

such as inappropriate termination of coolant injection. These aspects have been often neglected in the first-generation approaches.

2) ATHEANA provides very detailed procedures to find the reason why the unsafe actions associated with the HFE have been performed, i.e., the error-forcing context. For instance, ATHEANA presents a method in detail that can be used to identify the formal and informal rules the plant operators use (e.g., emergency operating procedure; to avoid going solid in the pressurizer or protect a pump upon its trouble alarm), and the reasons that make the operator believe that such rules are satisfied. This detailed method and procedures will be very useful particularly for retrospective analysis of a small number of human failure events. However, a large number of human actions or failure events should be analyzed for predictive analysis of human reliability such as MMI design evaluation. Hence, ATHEANA may be used only where a very detailed analysis, e.g., including diagnosis or cue time line, is needed.

3) ATHEANA is so PSA-oriented that it has many drawbacks as HRA-cum-PSA. For example, ATHEANA analysis begins with an HFE identified from PSA accident sequences analysis. This HFE is treated as a binary form of success and failure, and the accident sequences usually do not change by an occurrence of any type of human erroneous action. However, if a variety of human errors, such as post-accident commission error or cognitive error, are considered, the initiating event may evolve into such accident sequences that have not been predicted in the PSA. Hence, the ATHEANA method based on the HFEs from PSA model has such drawbacks that the consequences of human errors are limited by the pre-identified PSA accident sequences.

4) The theoretical background of ATHEANA seems rather weak for predictive analysis. Post-accident human erroneous actions, including errors of commission, are often caused by cognitive error. Thus human error analysis scheme or cognitive model developed in cognitive psychology or cognitive system engineering can be useful for post-accident human reliability analysis. Nevertheless, ATHEANA apparently does not take full advantage of these cognitive engineering-based models.

While ATHEANA focuses on identifying especially post-accident errors of commission resulting from error-forcing context and plant condition, CREAM puts emphasis on analyzing the causes of human actions, i.e., human cognitive activities. CREAM is based on the classification schemes of error modes and of various elements of the man, technology, and organization (MTO) triad, which includes person-related factors, system or technology-related factors, and organization-related factors.

The classification schemes can be used in either direction, forward or backward: the forward direction is used for predictive analysis or performance prediction, and the backward direction for retrospective analysis or event analysis (Figure 3). The appropriate element among the classified items is chosen taking into account the context under which the task is performed. We can use the classification schemes of CREAM in the forward direction because we have to estimate the human performance in the proposed MMI to validate the MMI design.

Figure 4 graphically describes how human performance for a task is predicted by the CREAM method. The CREAM process for human performance prediction is as follows:

1) The task, such as switchover to recirculation or feed and bleed operation, is selected from an event sequence of PSA or other similar analysis.
2) The task is analyzed by a method like hierarchical task analysis.
3) The work conditions, so called common performance conditions (CPCs), under which the task is performed are assessed. A total of nine CPCs are used in CREAM: a) adequacy of organization, b) working conditions, c) adequacy of MMI and operational support, d) availability of procedures/plans, e) number of simultaneous goals, f) available time, g) time of day, h) adequacy of training and preparation, and i) crew collaboration quality.
4) The cognitive demands profile is built to identify the specific demands to cognition in terms of a simplified set of cognitive functions, i.e., observation, interpretation, planning, and execution.
5) The probable or likely control mode is determined for each task element by integrating the effects of the specific CPCs for the given task on human reliability.
6) The likely cognitive function failure is identified in terms of the four cognitive functions mentioned in 4).
7) Finally, the cognitive failure probabilities for each task element and for the task as a whole can be estimated by first assigning the nominal cognitive failure probability (CFP) for each of the likely cognitive function failures, and then assessing the effects of the CPCs on the nominal CFP values.

As indicated in section 2 and Figure 1, the CREAM HRA method, especially for human performance prediction described above (Figure 4), can be used for integrated MMI design validation and design improvement verification. For example, consider the feed and bleed operation during loss of total feedwater accident at a pressurized water reactor. This task was analyzed using CREAM in an HRA benchmark study at the Korea Atomic Energy Research Institute (KAERI) [12]. The cognitive task analysis of the emergency operating procedure (EOP) for handling this accident identified 23 detailed task steps.

Following the task analysis, the various common performance conditions (CPCs) are assessed, e.g., the control panel information available to monitor, the complexity of the plans or means needed to achieve a task, and the number of simultaneous operations. Once the CPC analysis is carried out, the cognitive demands profile for the feed and bleed operation and the likely cognitive function failure type for each task element can be

Table 1. Cognitive Function Failure Types Used in CREAM

Cognitive Functions	Potential Cognitive Function Failure	
Observation Errors	O1	Observation of wrong object. A response is given to the wrong stimulus or event.
	O2	Wrong identification made, due to e.g., a mistaken cue or partial identification.
	O3	Observation not made (i.e., omission), overlooking a signal or a measurement.
Interpretation Errors	I1	Faulty diagnosis, either a wrong diagnosis or an incomplete diagnosis.
	I2	Decision error, either not making a decision or making a wrong or incomplete decision.
	I3	Delayed interpretation, i.e., not made in time.
Planning Errors	P1	Priority error, as in selecting the wrong goal (intention).
	P2	Inadequate plan formulated, when the plan is either incomplete or directly wrong.
Execution Errors	E1	Execution of wrong type performed, with regard to force, distance, speed or direction.
	E2	Action performed at wrong time, either too early or too late.
	E3	Action on wrong object (neighbor, similar or unrelated).
	E4	Action performed out of sequence, such as repetitions, jumps, and reversals.
	E5	Action missed, not performed (i.e., omission), including the omission of the last actions in a series ("undershoot").

identified. Table 1 shows the generic cognitive function failure types used in CREAM. For the feed and bleed operation task, the KAERI' s study identified seven interpretation errors that are likely to occur under the CPCs: two 'I1' interpretation errors (i.e., faulty or incomplete diagnosis), and seven 'I3' interpretation errors (i.e., delayed interpretation).

The KAERI' s study concludes that the likely cognitive errors predicted by CREAM correspond with the opinions of experienced operators and HRA experts, without going any further. However, to validate the MMI using CREAM for the feed and bleed task under a given specific scenario, one needs to proceed along with the analysis. From the assessment of the CPCs, the necessary adjustments for the dependencies between CPCs, and the determination of the combined effect on human performance reliability, the probable control mode can be identified in terms of strategic, tactical, opportunistic, or scrambled modes for the task as a whole or major task segments.

The least desirable situation corresponds to the scrambled control mode, and the most desirable situation corresponds to the tactical or strategic control modes. In situations where the CPCs are inadequate or inferior, the operators are likely to lose control and performance reliability is expected to be low. Inadequate CPCs may result from incompatible working conditions (such as glare on screens, noise from alarms, or interruptions from the tasks), inappropriate MMI, inappropriate procedure, and so forth. To validate the MMI using CREAM for the feed and bleed task, one should analyze in more detail those task segments for which the likely control modes have been identified as either scrambled or opportunistic. In the case where the operator's performance reliability is expected to be low especially because of inadequate MMI, for instance, then the relevant MMI support for the task segment, such as alarms, displays, and controls, should be thoroughly examined using a simulator, if available, to find potential improvements.

Particularly in view of its application to MMI design review, we can identify that CREAM has the following characteristics:

1) CREAM has been developed with its roots on the theoretical basis of cognitive psychology and cognitive engineering. As a method focusing on human cognition, CREAM shows a great potential for application to advanced MMI design review in which analysis of the operator's cognition is one of the most essential elements.
2) The method used by CREAM for analyzing and quantifying human errors is seemingly even more systematic and clear compared to that used by ATHEANA, at least as long as predictive analysis is concerned. As a result, we expect that, for performance prediction in the advanced MMI, using CREAM as a basic method will be more efficient than using ATHEANA from the viewpoint of resources and efforts needed.
3) A main advantage of CREAM classification system is that the same principles can be used for both retrospective and predictive analyses. However, CREAM was developed originally for retrospective analysis like ATHEANA. It appears that more work needs to be made to improve CREAM particularly for predictive applications, such as the MMI design evaluation. Furthermore, the CREAM classification system has not been developed with a specific application to nuclear power in mind. As a result, adapting the CREAM classification system to MMI design review is necessary.
4) Due consideration of the possibilities to recover human erroneous actions is extremely important in qualitative and quantitative analyses of human reliability. It appears that recovery factors are not explicitly taken into account in CREAM. In order to use CREAM for advanced MMI design evaluation, changes in the dynamic context and the resulting variation of the recovery possibilities should be thoroughly investigated.

5. Application of HRA to an Integrated Validation of Advanced MMI

Our insights on how the HRA methods, in particular ATHEANA and CREAM, can be applied for an integrated validation of advanced MMI are summarized below:

1) Before contemplating the application of HRA methods to the advanced MMI design review, one may define, first of all, the design objectives of MMI from a standpoint of human reliability as follows.

- Maximization of Human Performance Capabilities: The MMI should be designed such that the human performance capabilities can be maximized by optimizing such factors as human factors, ergonomic factors, organization factors and performance shaping factors (PSFs). Special consideration should be given to providing the operators with operator aid systems, e.g., computerized emergency operating procedure (EOP) system or alarm processing system, so that they can carry out their emergency tasks effectively.

- Minimization of Human Error Possibilities: The MMI should be designed such that the impact of human erroneous actions on plant safety is minimized by identifying and implementing the method by which various human errors, such as omission errors, commission errors, or cognitive errors, can be reduced. The HRA method discussed above, e.g., CREAM or ATHEANA, can be a great help in this respect.
- Maximization of Recovery Possibilities of Human Errors: The MMI systems like annunciator system, safety parameter display system (SPDS), or large display panel (LPD) should be designed such that they can enhance the recovery possibilities of human erroneous actions that may be committed before or after an accident occurs in the plant.

2) In order to evaluate the MMI design, all the factors that may influence the human performance or the possibilities of human erroneous action occurring should be considered together. In CREAM these factors are collectively called man, technology, and organization (MTO) triad, as discussed earlier. ATHEANA also considers these factors to some extent, but not as systematically as in CREAM where they are treated with a detailed and well organized classification scheme. Hence, CREAM appears to be more useful as compared to ATHEANA for the purpose of MMI design review.
3) In addition, what impact the availability of an operator aid system in the control room makes on the human reliability also should be estimated for the MMI design review. For the consequence analysis of this sort also, CREAM will be more useful than ATHEANA. Hence, the usefulness of CREAM for this purpose may be enhanced if the domain-specific information and knowledge are supplemented to CREAM.
4) When analyzing human action in terms of an HRA method, one tends to do it within the boundary of PSA; namely, only those human actions that are identified important in the accident sequence analysis are usually considered. In reality, the initiating event or accident may evolve into those sequences that have not been predicted in the PSA because of an occurrence of human erroneous action such as commission error or cognitive error. Hence, the analysis of human reliability should not be limited within the boundary of binary treatment of human action.
5) Post-accident human reliability typically has been analyzed in terms of an EOP to cope with a specific accident or a severe accident guide (SAG) for specific accident management strategies. For instance, only an event-based EOP for steam generator tube rupture or an SAG for reactor cavity flooding used to be used in evaluating human performance following an accident. However, when responding to an accident using EOP, the operator does not rely on only the event-based EOP. If a more serious event happens while the event-based EOP is used, then he may transfer to a symptom-based EOP to cope with it. Therefore, one should consider this kind of dynamic context to analyze post-accident human reliability. Neither ATHEANA nor CREAM incorporates an explicit method to deal with the dynamic context; thus, a further study is needed in this area.

6. Concluding Remarks

In the advanced MMI, considerable change is expected as regards the role of plant operators and their tasks. As a result, a new type of commission error or cognitive error that can adversely impact the plant safety may be introduced into the advanced control room. Therefore, it is important to identify the error-prone situations or potential human errors in advance to resolve human engineering deficiencies that may exist in the MMI design.

In this paper we discussed the applicability of human reliability analysis to support the MMI design review process. Two promising HRA methods, i.e., CREAM and ATHEANA, have the greater potential to assist the review process, as compared to the so-called first-generation HRA methods.

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