Study on Analysis Method of Operator's Errors of Situation Awareness in Digitized Main Control Rooms of Nuclear Power Plants

Pengcheng Li[a], Li Zhang[a,b], Licao Dai[a], Jianjun Jiang[a], and Difan Luo[a]
[a] Human Factor Institute, University of south China, Hengyang, People's Republic of China
[b] Hunan Insitute of Technology, Hengyang, People's Republic of China

Abstract: Situation awareness (SA) is a key element that impacts operator's decision-making and performance in nuclear power plants (NPPs). The subsequent complex cognitive activities can not be correctly completed due to errors of situation awareness (ESA), which will lead to disastrous consequences. In order to investigate and analyze operator's situation awareness error in digitized main control room (DMCR) of the nuclear power plants, the model of ESA is established, the classification system of SAE is developed based on the built SAE model, and the method of ESA is also constructed on the basis of the observation of simulator and operator surveys. Finally, a case study is provided to illustrate the concrete application of the method. It provides a theoretical and practical support for the operator's SAE analysis in the digitized main control room of nuclear power plants

Keywords: Situational Awareness Error; Analytical Method; Digitized Main Control Room

1. INTRODUCTION

Situation awareness (SA), which is used within human factor research to explain to what extent operators of safety–critical and complex real systems know what is going on the system and the environment, is considered a prerequisite factor for effective decision making and performance[1]. In the accident disposition process of complex industrial systems, operators can not correctly complete the following complex cognitive activities which will bring disastrous consequences because of loss of situational awareness (LSA). For example, the Three Mile Island nuclear accident, the operator failed to understand the state of primary loop in Three Mile Island nuclear accident [2], and pilots lost the proper understanding of flight status and so on in the variety of aviation accidents[3]. Endsley [4] found that the cause of 88% of commercial aviation accidents caused by human error has some kind of connection with LSA. Jones and Endsley [5] pointed out that 69% of incident reports contain information gathering errors of SA of air traffic controllers by incident report analysis occurred in the field of air traffic control. Therefore, SA is a key element that impacts operator's decision-making and performance, and ultimately may lead to accidents.

With the improvement of level of system automation, operator's errors of situation awareness (ESA) become increasingly prominent. In this light, since the late 1980s, research on SA continues to gradually receive a considerable amount of attention from the high-risk field of civil aviation, air traffic control, nuclear power plants, hospital etc. It has become a hot research, and a number of theoretical model related to SA are established, in which the famous one is the SA model established by Endsley[6] based on information processing method. The model divides SA into three levels: Perception of the elements in the current environment (Perception), comprehension of the current situation (Comprehension) , and projection of future status (Projection), and the factors affecting SA are identified, which includes individual factors and system / task factors (see Figure 1). Endsley's SA model seems generic and comprehensive, as it is based on general cognitive processes, and provides a broad theoretical analysis framework for many application areas, but it doesn't in detail describe the cognitive processes and influencing factors of SA. For example, the identification of causes of system malfunction, it should belong to SA. Therefore, it is not conducive to the classification and investigation of ESA, and it is also difficult to make specific preventive measures to prevent ESA.

In addition, with the rapid development of computer, control, and information technology, the instrumentation and control (I&C) system of nuclear power plants (NPPs) is transformed from traditional analog control to digital control, the man-machine interface (MMI) in control room is transformed from the traditional monitor and control board to the computer-based workstation. In this respect, the role of operator is changed from the past "manipulator" to "monitor and manager", and the operating environment in advanced digital main control room (MCR) is very different from the

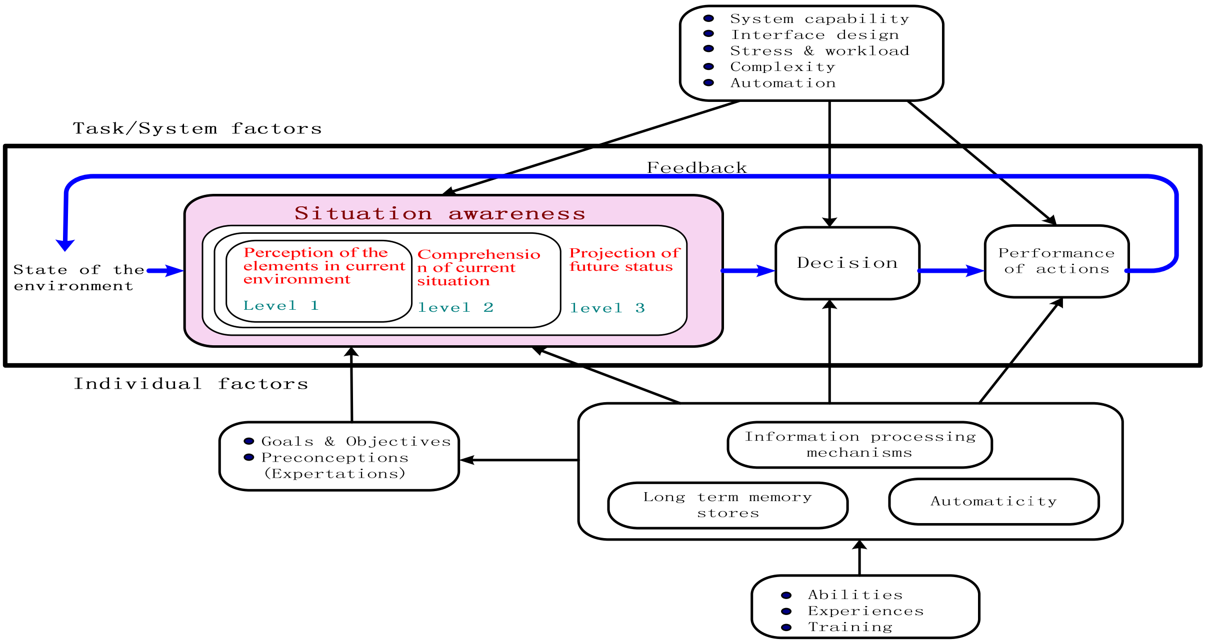

Figure 1 Endsley's Three-level model of situational awareness

environment in traditional analog control room. Digital human-system interface (HSI) has changed the operating context including information display (a huge amount of information with limited display), procedures (computerized procedures), control (soft control), task (interface management tasks) and so on, which may bring new human factor problems, especially operator's SA problems [7]. For example, the control panels in conventional control room are spatially fixed, and information displays on panels are visual, it is useful to understand the status of the entire system of NPPs for the operators, but the positions of information showed by modern computer-based display are not fixed, the relationships among information are divided, information displayed on screen is more abstract and upper information, and computer-generated information displays are not limited by physical space, the amount of displayed information is huge etc., but information that can be directly observed is limited through computer screen, a lot of dynamic information is hidden. To obtain plant state information, operators must implement so-called "interface management tasks" such as navigating, configuring and arranging etc.,[8]. The "secondary tasks" related above will increase operators' cognitive load, consume their attention resources and generate a "keyhole effect "[9]etc. , thus affect operator 's SA, which makes operator out-of-the-loop [10]. Therefore, SA issues may be more prominent in digital main control room of NPPs, digitization of HSI has changed the operator's SA cognitive mechanisms, so the traditional theoretical models of SA are difficult to meet the current requirements of ESA analysis. Therefore, we attempt to establish a framework of ESA analysis to guide ESA analysis.

2. OPERATOR'S SA MODEL IN DIGITAL MAIN CONTROL ROOMS

2.1. Operator's SA in Digital Main Control Rooms

With the development of technology and improvement of automation level, operator's major tasks represent as cognitive tasks in complex social-technical systems such as NPPs, including: (1) monitoring and detection, (2) situation assessment, (3) response planning, and (4)response implementation [11]. Endsley[6] views SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future". According to Endsley's definition, situation awareness process includes a series of cognitive activities (including at least monitoring and detection, situation assessment), these errors related to the cognitive activities are part of ESA. In this light, we think that SA is “operators actively try to construct a coherent, logical explanation to understand the unit/system state and what is going on by various information processing on the basis of the collected parameter information in digital NPPs”, this series of cognitive processes and assessment results are called SA.

Operator’s behavioral characteristics of SA are identified by field observations of simulator training and operator interviews in digital main control room of NPPs. In digital control system of NPPs, many of complex tasks are replaced by automation (e.g. whether high head safety injection operate? whether loss of feedwater? Whether at least one steam generator with activity< high measurement limit? etc.) due to increased automation level, which are diagnosed and determined by operator support system. In the information collection processes of SA, when an abnormal event occurs, one or more alarms will appear, operator will examine the occurred alarm and its reasons to take appropriate measures to deal with it. Information that operator needs to monitor is provided by computer-based display screen, the information that requires operator monitoring is more dispersed. For example, when operator needs to collect the failed components to determine the failure state of a system, operator needs to monitor the status of multiple parameters (e.g. error signal input to controller, requirement information of components, and actual state of components, etc.). In general, in the stage of monitoring and detection, the operator’s task is mainly to gather information, including single information and more information. The operator's cognitive activity is monitoring/detection by “seeing/listening”, “information searching or location”, “information recognition” and “information verify” for individual information, and their activities are information filtering, screening, etc. for more information, which are combined into a cognitive function, that is “multiple information gathering”. Further, in case of an accident, since the state-oriented procedure (SOP) is used in digital control room of NPPs, operator 's tasks need to implement are more simple tasks in general, mainly including information comparison (such as temperature , pressure comparison), simple judgment (such as acknowledge the alarms occur? At least one stream generation is isolated?), a simple calculation (the pressure difference is greater than 10 Bar.g between two SG?) etc. Therefore, the assessment for these simple tasks is called “information comparison”, i.e., the parameters identified in the monitoring process compare with the parameters procedures required, and to confirm the state of components. Furthermore, the combination of several simple tasks can identify the status of system components (such as to determine whether the RCP (French acronym, namely reactor coolant system) pump shuts down, the determination made by operator needs to judge a series of standards), the comparison result of single task/parameter is obtained through comparison between actual data and requirement data, then the larger component or subsystem state is identified by information integration (including understanding and reasoning), the series of cognitive processes may be relate to cognitive functions which involve “information comparing”, “information integrating”, and “state explanation”. For diagnosis of more complex incidents (although the DOS (Document of orientation and stabilization) procedure does not need operator to determine what kind of accident occurs, but the judgment of six key parameters and their combinations are also complex), it needs to identify the state of system according to the combination of state of various subsystems, the process also relates to the cognitive functions related above. Similarly, for different fault, failure and incident or accident, their causes need to be identified, it is conducive to the selection and development of response plans. Furthermore, for novel situation and other, the current state of system needs to be assessed and the next state needs to be predicted by deeper reasoning according to their own knowledge and experiences, as well as limited data. Similarly, the severity of accident, the future development trend of state of component, subsystem and system need to make projection. Therefore, the cognitive functions of operator in situation assessment process also involve “cause identification”, and “state projection”. Therefore, the model of SA is built on the basis of information processing theory and cognitive task analysis as shown in Figure 2.

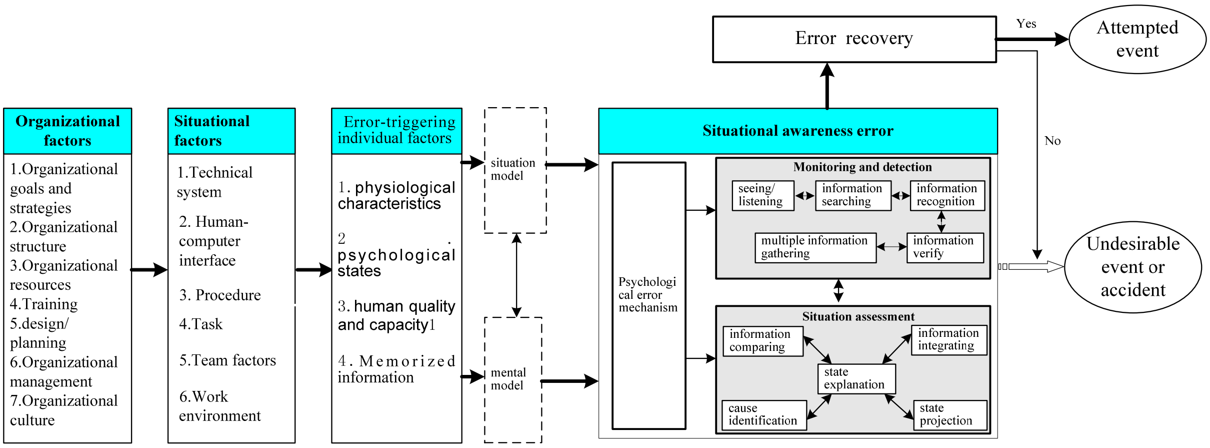

Figure 2 Operator’s SA analysis model

2.2. Influencing Factors of Operator’s SA in Digital Main Control Rooms

Reason [12] writes: “Human error is a consequence, not a cause. Errors are shaped and provoked by the upstream workplace and organizational factors.” ESA is no exception. As far as influencing factors of human errors be concerned, according to Want’s viewpoint [13]: the antecedents triggering human errors (or unsafe actions) are psychological precursors, such as human motives, plans, expectations, attention, and the way of reasoning, etc., the influencing factors causing psychological precursors are environmental conditions, which is called as latent failures. These latent failures in principle are under management and control of organization, however, when the organization’s management and control fails, it will cause an accident. Therefore, in order to identify the root causes of organization causing ESA and prevent it from the source of ESA. The model of influencing factors of SA is established based on the established organization-oriented “structure-behavior” model [14] and context analysis of digital main control room of NPPs, it is shown in Figure 2.

The plant state is influenced by human behavior, human behavior is influenced by the states of the mind and body as well as the plant state, and the mental state is influenced by both the plant state and human behavior[15]. Operator’s SA is not only affected by external dynamic contextual factors but also by internal factors (such as personnel quality and capability), and there are complex interactive relationships between the internal/individual factors and situational factors as well as organizational factors (such as training), we can think that the individual factors are the direct factors causing ESA because operator’s physical, psychological and other factors (the deficiencies of inherent characteristics such as knowledge) are influenced by external contextual factors, when they are in imbalance state, which will result in human cognition and action errors. Although it is difficult to change person's own conditions to improve person’s cognition and action reliability, we can control the states of situational and organizational factors to improve person's cognitive or behavioral reliability because the qualities of individual factors are mainly affected by situational factors (such as poor man - machine interface) and organizational factors (such as safety culture), so we can improve person's cognitive or behavioral reliability to reduce ESA by controlling the qualities of situation situational and organizational factors, and it will reduce the action errors (active errors). Therefore, the established influencing factor model includes organizational factors, situational factors and individual factors. The ESA is influenced by individual factors, and the individual factors are influenced by situational factors, as well as situational factors are influenced by organizational factors, but do not rule out the existence of jumping affecting between factors. For example, the individual factors are directly affected by organizational factors (such as the improper plan of work will lead to continuous work, thus it will cause operator’s fatigue).

The cognitive field, situation assessment, involves two related concepts: the situation model and the mental model [16]. Situation model is operator’s understanding of the specific current situation, and it is constantly updated as new information is received. The mental model is built up through formal education, system-specific training, and operational experience, and it is stored in the brain and relatively fixed, and it is represented in the knowledge bases of long-term memory (LTM). The situational awareness process is operators use their general knowledge to interpret the information they observe and understand its implications to construct a situation model, the current state of component/system/plant is understood by matching the situation model and mental model. If the both models are correct, and each other matches well, then the reliability of situation assessment will be very high. If the situation model (for example, there is not enough information is provided) or mental model (for example, there are limitation in knowledge) has some flaws, or incorrect matching, then ESA will occur. The operator's understanding of outside state of system (situation model) is impacted mainly by external contextual factors, including "system factors", "computer-based human-system interface factors", "environment of main control room", "team factors", "task factors" and "procedure factors" and so on. For example, the level of automation of systems may affect operator 's situational awareness, Kaber and Endsley [17] indicates operator can not promptly and accurately obtain some important information, which will lead to wrong cognition and wrong manipulation, eventually causing serious consequences due to increased levels of automation, it is known as so-called "human out-of-the-loop performance". Out of the loop performance problems are characterized by a decreased ability of the human operator to intervene in system control loops and assume manual control when needed in overseeing automated systems. In addition, the mental model is influenced by training and education including ways of training, training programs, training tools, required resources allocation of training, special education support, supervision of training process, evaluation of training effectiveness, quality assurance of training and own knowledge and practical experience etc. Furthermore, situation model and mental model, and matching process between them are also affected by the inherent limitations of individual information processing including attention (such as attention tunneling), memory (such as memory capacity limitations), expectations(something expected to see) , goals (goal-driven information searching) and ways of information processing and strategies (mode matching, story building process, meta-cognition, etc.) [17, 18].

3. THE CLASSIFICATION FRAMEWORK OF ESA ANALYSIS

A classification scheme, as an ordered set of categories, is necessary both to define the date that should be recorded and to describe the details of an event, and it is basis for ensuring consistency of results of event analysis.

3.1. Classification of ESA and Psychological Error Mechanism

ESA can be used error modes of SA to describe, and it is closely related to failures of human cognitive function, and can be expressed as cognitive function failures and failure modes. According to the definition of SA related above, SA processes majorly include the cognitive processes of monitoring and situation assessment. The cognitive functions include "seeing/listening", "information searching or location", "information recognition", "information verify" for individual information and "multiple information gathering" in monitoring process. Furthermore, the cognitive functions involve "information comparing", "information integrating", and "state explanation", "cause identification", and "state projection" in situation assessment process. In the digital main control room of NPPs, operators need to "compare" the factual information and procedure required information to identify whether the parameter is abnormal, in which operators are prone to make errors such as comparing error, no comparing or delaying comparing. Similarly, for other cognitive function in SA, there are also other failure types of cognitive function, we use keywords such as "none", "late", "wrong" and "loss" etc. to describe. The specific categories of ESA are shown in Table 1.

Operator's cognitive function failure has its corresponding psychological error mechanisms (PEMs). PEMs describe the psychological nature of the cognitive function within each cognitive domain/process, the cognitive biases that are known to affect performance. If we can find PEMs corresponding to different cognitive failure modes, then it is useful for error reduction and mitigation. However, they may require significant understanding of psychological aspects of an error, which may not always be obtainable from incident reports, and the existing psychological analysis tools are not sufficient support a deeper understanding of psychological mechanisms of error. The PEMs for cognitive domain of monitoring and situation assessment are identified on the basis of the results of previous studies [19-21], and they are listed in Table 1.

Table 1: The classification of ESA

Cognitive processes	Cognitive activities	error modes	Specific errors (relevant keywords)	Psychological error mechanism
monitoring/ detection	C1:Seeing/Listening	Seeing/Listening error	-None,late,wrong, loss	Expectation bias; perceptual confusion; distraction / preoccupation; task overload; perceptual tunnelling; spatial confusion; low vigilance, attention detection not in time, visual fatigue; frequency preference; keyhole effect, etc.
	C2:Information searching or location	Information searching or location error	-None,late,wrong	
	C3:Information recognition	Information recognition error	None,late,wrong	
	C4:Information verify	Information verify error	None,late,wrong	
	C5:Multiple information gathering	Multiple information gathering error	-Omission, Irrelevant, Insufficient, Redundant	
Situation Assessment	Information comparing	Information comparing error	-None,late,wrong	Lack of knowledge; no considering side effects; integration failure; false assumption; misinterpret; cognitive fixation (halo effect); similarity interference; memory block; memory capacity overload; loss of positions; keyhole effect, etc.
	Information integrating	Information integrating error	-None,late,wrong	
	State explanation	State explanation error	-None,late,wrong,loss	
	Cause identification	Cause identification error	-None,late,wrong	
	State projection	State projection error	-None,late,wrong	

3.2. Classification of Influencing Factors of SA

With reference to the classification of influencing factors of SA, which have been studied by some researchers[22-25], but their researches are lack of hierarchical, systematic and comprehensive, such as their classifications of influencing factors are not specific and detail enough to describe the characteristics of influencing factors, some studies only focus on individual factors effects on SA, and there is no considering the root causes of organization etc. Therefore, the detailed classification of organizational factors, situational factors and individual factors is built based on collected references including the first generation techniques such as THERP (Swain and Guttmann, 1983), HCR(Hannaman et al., 1985), SLIM (Embrey, 1984), HEART (Williams,1992), the second generation techniques such as CREAM (Hollnagel, 1998), ATHEANA (Cooper et al., 1996), CAHR (Sträter, 2000) and third generation HRA techniques such as OPSIM (Dang, 1996), IDAC (Chang, 2007) are collected, and also consider the classification of performance shaping factors (PSFs) in the CSNI classification (Hollnagel, 1998), SPAR-H (Gertman et al., 2005) and the HRA good practices (Kolacakowski et al., 2005), and combine with the study results of classification of organizational factors from the previous studies (Li et al., 2009)[14]. The classification tries to follow five principles of classification: (1)concrete, (2)assessable and measurable, (3) non-repetitive and non-cross; (4)consistency, and (5)comprehensive. The specific classification of organizational factors may be a process, such as planning formulation, task allocation, may indicate a state, such as lack of goals, the number of personnel, may indicate the certain property of upper-layer factors, such as the style of training, etc., as shown in Table 2. It should be noted that the above classification system basically considered the influencing factors of human activities, not just for the influencing factors of SA, but we think that the classification of influencing factors is also applicable for the analysis of ESA.

Table 2: The classification of individual, situational and organizational factors

Influencing factors	**Subclass**	**Specific factors**
Individual factors	Psychological state	Cognitive modes and tendencies: alertness, attention to current task, attention to surrounding environment, cognitive bias, Stress：frustration, conflict, pressure, uncertainty. Strains and feelings: time-constraint load, task-related load, non-task related load, passive information, confidence in performance. Perception and appraisal: perceived severity of consequence associated with current diagnosis/decision, perceived criticality of system condition, perceived family with situation, perceived system confirmatory/contradictory responses, perception of alarms(quantity, intensity, importance),perceived decision responsibility, perceived complexity of strategy, perceived task complexity, perception of problem-solving resource , awareness of role/responsibility, done quickly psychology, habit psychology. Intrinsic characteristics: motivation (desire, demand), attitude, morale, character and personality, self confidence, problem solving style
	Physiological state	Suddenness of onset, pain or discomfort, fatigue, hunger or thirst, physical movement constriction, lack of physical exercise, disruption of circadian rhythm, sensory loss, individual size / body condition
	Memorized information	None or incorrect of Recall perceptual information, none or incorrect of memory of previous execution action, none or incorrect of memory of current execution action (diagnosis, action and results), none or incorrect of memory of prospective execution action sequence, none or incorrect of memory of the stored information(procedural and declarative knowledge)
	Quality and capability	Knowledge, experience, skills / capacity, social roles, and level of moral
Situational factors	System	Degree of automation, the complexity of system, redundancy of system, system reliability, software reliability, compatibility and coupling degree of system configuration, inspection and test of output of system , system feedback, response speed/delay of system, number and speed of information presentation, information interference, number of simultaneous goals, required judgment beyond level of skill and experience, time stress/available time determined by system design
	Human - computer interface	Monitor and controller reliability, structure relationship of screens, range of display, display precision, display information cognizability, display information understandability, accessibility of control equipment , operability / availability of control equipment, accuracy of controlled location, requirement of special tools, complexity of interface management tasks，information display format, amount of information displayed, consistency of information in different displays, cognizability of software control icon, location of soft control icon on display , ease of operation of soft controller , type of soft control, data input and state feedback of controller, ease of discrimination of alarm, easy of search of alarm, keyhole effect
	Task	Perceptual requirements, motor requirements(speed, strength, precision), anticipatory requirements, interpretation of task, task complexity, narrowness of task, frequency and repetitiveness of tasks, task criticality, required long-term and short-term memory, calculation requirements, results feedback (knowledge of results), task type (dynamic VS step-by-step activities), task novelty, task speed requirements, high jeopardy risk, threats (failure, loss of job), nature of task (monotonous, degrading or meaningless work)
	procedure	Format or type of procedure, logic structure, forms of presentation, function / availability / validity of procedure, complexity, level of detail, accuracy requirement to activity, adequacy and integrity of description of warnings and cautions, activity criterion, understandability of procedure , interpretation margin, number of steps, required time for completion, clarity of instruction and terminology, level of standardization in use of terminology, decision making criterion, number of logical conditions(branches), number of simultaneous tasks
	Environment	Physical access, temperature, humidity, air quality, radiation, lighting, Color, noise , vibration, degree of general cleanliness, G-force extremes, atmospheric pressure extremes, oxygen insufficiency, external interference / distraction events
	Team factors	Team structure and level of personnel allocation, type of team communication, quality and validity of communication, team cohesion, team leadership, team cooperation and coordination, dynamic characteristics of team, role and responsibility of team
Organizational factors	Organizational Goals and strategies	Organizational objective (safety, performance): lack of objective, integrity objective system, consistency of objective system, priority of objective system, objective specificity, contradiction between current objective and long-term objective, Strategy: organizational policies/systems, formulation of high level plans, work methods/strategies, centralization of organizational decision-making, priority of management, problem identification and solution, determination of organizational structure, responsibilities, authority, Organization/workshop practices
	Organizational structure	Number of staff, control range, number of organizational level, location of decision / authority , roles and responsibilities, authorization, communication paths
	Organizational resources	Information resources: superior instruction, information of analysis method, information of process, manual. of activities, methods, tools. Material resources: equipment, tools, parts, materials Human resources: employee selection, performance evaluation, reward / incentive. Economic resources: available funds .Time resources: effective time, available time. Other resources: such as space resources
	Organizational Management	Organization: task allocation, personnel allocation, resource allocation, time arrangement, shift organization, work preparation, staff placement. Management: level of management such as human resources management .Control: supervision, control (such as quality control), verification and evaluation. Leadership: Leadership. Coordination: cooperation and coordination
	Education / Training	Way of training, training programs, training tools, required resources allocation of training, special education support, supervision of the training process, evaluation of training effectiveness, quality assurance of training.
	Organizational culture	Organizational climate: organizational cohesion, organizational knowledge, organizational learning, information sharing, sense of belonging of employees, group identity. Safety culture: tradeoff between safety and economy, safety standards and rules, safety attitudes, safety practices, safety measures, experience feedback, violations, documentation.
	Organizational plan / design	Strategic planning, safety planning, objective design, system design, work process design, programming/procedure design, work design.

3.3. Classification of recovery of ESA

Human errors are reduced by "error suppression" approach in the past, but a lot of practice shows that it is difficult to completely eliminate human errors. Another approach that may be a sensible way of combating the human error problem in high-risk technologies is error detection and correction. Error recovery includes three processes[26]: (1) error detection; (2) error explanation; and (3) error correction. There may exist in a variety of failures in error recovery process. Therefore, the classification of error recovery failure is determined according to the process of error recovery, as shown in Table 3.

Table 3: The classification of failures of error recovery

Error recovery type	Error recovery sub-type		description
Error detection	Self-examination	Detect mismatch between expectations and outcomes	Difficulties in perceiving or attending to actual outcomes and setting-up or remembering expectations about effects can result in failures of detection due to job factors such as poor interface design, high workload etc.
		Compare effects of equipment failures& self-produced errors	Biased attitudes and responsibility of explaining away errors can impede detection, the undesired outcomes can be easily attributed to equipment rather than one's own performance.
		Detect mismatch between plans and executed actions	Action-based detection takes place by a perception of some aspect of the erroneous action either auditorially, visually, or proprioceptively.
		Detect mismatch between intentions and plans	In the conceptual or planning stages, operator doesn't recognize wrong intentions(i.e. higher-level goals), or doesn't recognize the formulated plan is not suitable for achieving the goals etc.
	External examination	System feedback failure	System does not provide error externalization functions or poor externalization functions
		Error detection failure by supervisor	External personnel's monitoring, evaluation and communication each other etc. are not sufficient
Error explanation	Locate error in the interpretation of the situation		To establish error corrective plans, operator need to try to identify or explain the causes of the error, in which it may be produce explanation error due to available time and knowledge etc.
	Locate error in goals or plans		The errors in goals or plans are not identified because of limited time available and so on.
	Locate error in the specification of the task sequence		The errors in task sequence are not identified because of limited time available and so on.
Error correction	Re-assess situation		Situation reassess errors may occur during the re-evaluation of the state
	Develop corrective plan		After reassessment of the situation, the corrective plan errors may occur in developing corrective plans due to less time available ect.
	Execute corrective plan		The corrective plan is not successfully implemented

4. ANALYSIS METHOD OF ESA

The retrospective analysis method of ESA consists of the following five steps, as shown in Figure 3.

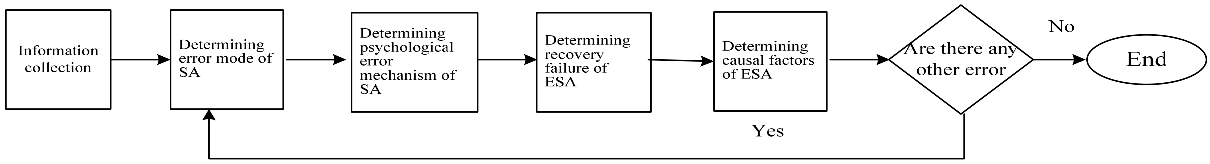

Figure 3 The analysis procedure of ESA

(1) Information collection. Using structured information collection method, which includes task analysis, goal-means analysis, cognitive function analysis and contextual analysis. Task steps, type, structure are determined by task analysis, and personnel, system, components and their relationships etc. are determined. Goal-means analysis focus on tasks or subtasks itself , the task goals and required methods and resources achieving task goals etc. are determined by Goal-means analysis; Cognitive function analysis is the determining of required cognitive functions related to SA to complete a given task, the classification of cognitive function of SA can be used to cognitive function analysis. Contextual analysis is a process of collecting and integrating the macroscopic contextual information on the given task. It includes the determining of task scenario, system/subsystem or components state, work environment and organization and management information etc.

(2) Determining error mode of SA. The most likely SA error mode characterizing human ESA id determined according to the detailed classification of ESA and the collected information, and we can also find a reasonable ESA by reasoning and argumentation if ESA is not very obvious.

(3) Determining psychological error mechanism of SA. The psychological error mechanism of SA is determined by reasoning according to the identified ESA and characteristics of errors recovery failure. The identification of psychological error mechanism of SA helps to understand the specific task context how to affect human cognition and behavior, and helps to find the causal factors triggering ESA and prevention of human error.

(4) Determining recovery failure of ESA. The possible recovery failure of ESA is identified through checking one by one according to the identified error mode of SA, and the classification of error recovery failure.

(5) Determining the causal factors of ESA. Based on analysis related above and investigation and verification of contextual environment, the reasons can be found in the corresponding classification of influencing factors, and can date back to the root cause of organization. If there are other ESA in an incident, a similar analysis will be continued until all of ESA are completed.

5. AN EXAMPLE

A case, namely “the high-high signal of water level of 2nd steam generator (SG) of 4th unit of Ling Ao NPP superimposing the signal of P7 causes shutdown of reactor”, is used to demonstrate the proposed ESA analysis method.

5.1. Event Summarization

May 21, 2011, the 4th unit of Ling Ao NPP falls back to hot shutdown due to the water quality in secondary circuit. May 22, the unit goes critical after restoring water quality in secondary circuit, the reactor power rises to 8.0% Pn, and the feed-regulating valves and rotation speed of main feed pumps of three steam generators are in manual control. 17:53, the team leader of unit finds “L4ARE001MP” (steam generator feed water and vapor pressure difference) is low (1.2bar, far less than the required value 4.2bar), so he requires the operator to adjust the speed of feed pumps to rise pressure difference in order to control rotation speed control as soon as possible, then the feed pumps are put into operation in automatic mode. The signal of high-high water level (P14 signal) of the 2nd steam generator emerges when the operator raises rotation speed of feed water pumps, and at the same time, the reactor power fluctuate over 10% Pn, the signal of P10/P7 occurs. The reactor automatically shutdowns because of the signal of high-high water level superimposing the signal of P7. Then the operators implement DOS procedure to the unit. 18:57, the unit is in stable state and exits the DOS procedure.

5.2. Information collection

The critical path of event is identified and built by information collecting and analyzing as shown in Figure 4, we can see the incident mainly includes two human errors from Figure 4, that is, the operator of primary loop can not correctly adjust the opening degree of small valve of ARE (Feedwater flow control system), and the operator of secondary loop adjusts the rotation speed of APA102 pump (Motor-driven feedwater pump system) too fast. Then task analysis is carried out for a specific human error to determine the required cognitive functions and cognitive errors for completing the task. Furthermore, contextual environment analysis is carried out to determine the cause of errors. We take "the operator of primary loop can not correctly adjust the opening degree of small valve of ARE" as an example to demonstrate information collection. The following is collected basic information:(1) Task——the manual adjustment of three small flow control valve of ARE; (2)Goals and means—— Controlling water level of three SG control, which needs basic manual operation; (3)Required cognitive function—— detection (detect water level changes) , explanation (state of water changes), decision (adjust to what extent of water level) and execution (implement of adjusting response); (4)Contextual environment—— SG water slowly declines, the man-machine interface related to valve, which waits for verification of results.

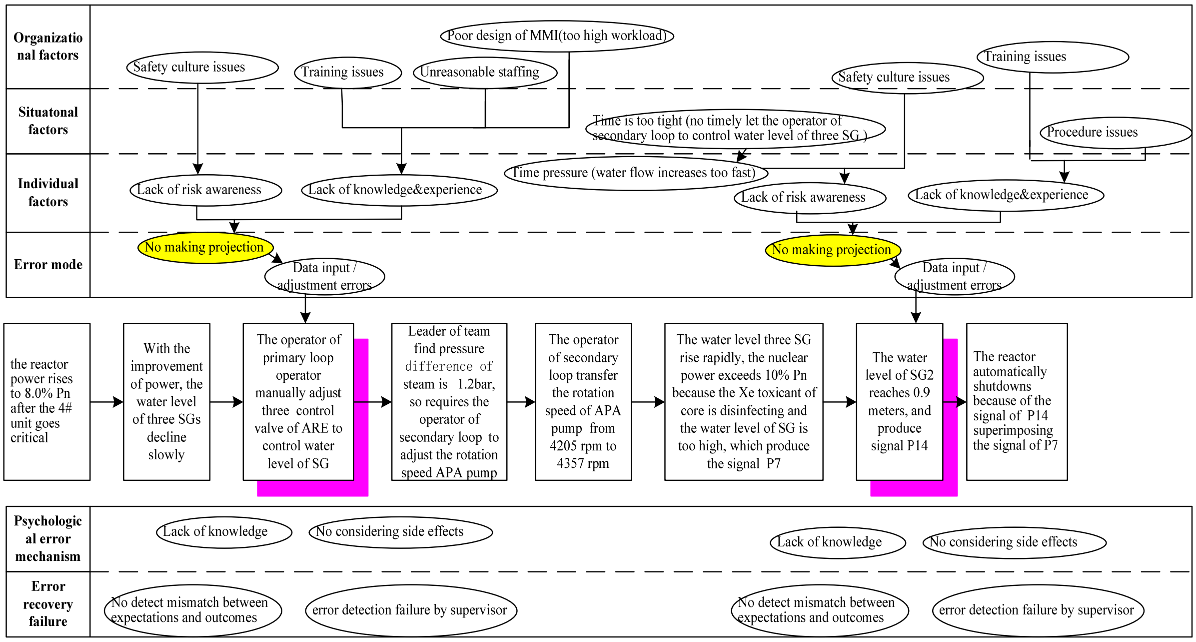

Figure 4 The event and cause factors analysis of the application case related above

5.3. Determining action and cognitive error modes

With reference to "the operator of primary loop can not correctly adjust the opening degree of small valve of ARE", the action error mode is apparently "adjustment error". The cognitive cause causing action error is "operator does not make projection", that is operator does not predict whether this adjustment produce an adverse effects on the system when the opening degree of the valves is adjusted to 80%.

5.4. Determining psychological error mechanism

The psychological error mechanism obviously is "lack of knowledge" because the operator does not assess the rationality of opening degree, and he does not consider the risk of 80% opening degree of the valves, its psychological error mechanism can be thought as "no considering side effects" by analysis.

5.5. Determining error recovery failure

According to the classification of error recovery failure and the identified human error modes, we can obtain the error recovery failure "detect mismatch between expectations and outcomes" corresponding to the error "the operator of primary loop can not correctly adjust the opening degree of small valve of ARE ". Similarly, another error recovery failure is identified by contextual analysis, which is "error detection failure by supervisor" belonging to classification of "External examination", because the director of team does not diction the operator's error.

5.6. Determining causal factors of human error

According to the operator's cognitive and action error modes and contextual environment analysis, the individual factors causing human error are "lack of knowledge and experience" and "lack of risk awareness". The causes of "lack of knowledge and experience" are attribute to "poor training", which belong to organizational factors, and "poor man-machine interface" which belong to situational factors, because the secondary loop operator's task load is too large, which may be due to poor man-machine interface, so secondary loop operator task load is too large , so that the primary loop operator is arranged to do the secondary loop operator's work which does not belong to him and does not know well. The cause giving raise to "lack of risk awareness" is due to "poor safety culture". In addition, the investigation results of another human error can be obtained by the same analysis procedure as shown in Figure 4.

6. CONCLUSION

SA issues are more prominent in digital control systems of NPPs, and it is a key element impacting operator's decision-making and performance. The analysis method of ESA is also an important part of human error analysis. The cognitive functions of SA are identified based on task analysis and field simulator observation in this paper, and the classification system of ESA is built according to cognitive function of SA. ESA are placed in a more all-sided contextual environment to establish the model of SA from organizational perspective, and the model-based classification system used to analysis of ESA is provided from inherent cognitive mode, the psychological error mechanism, error recovery failure to external causal factors etc. It combines "person approach" with "system approach", and the classification system is more detailed and concrete than the traditional classification system., and provides a structured analytical framework to identify the root cause of organization causing ESA. Therefore, the established analysis method of ESA will provide theoretical basis and practical application guidance for ESA analysis, prevention and reduction in digital control system of NPPs.

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