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A Model of the Operator Cognitive Behaviors During the Steam Generator Tube Rupture Accident at a Nuclear Power Plant

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Abstract

An integrated framework of modeling the human operator cognitive behavior during nuclear power plant accident scenarios is presented. It incorporates both plant and operator models. The basic structure of the operator model is similar to that of existing cognitive models, however, this model differs from those existing ones largely in two aspects. First, using frame and membership function, the pattern matching behavior, which is identified as the dominant cognitive process of operators responding to an accident sequence, is explicitly implemented in this model. Second, the non-task-related human cognitive activities like effects of stress and cognitive biases such as confirmation bias and availability bias, are also considered. A computer code, OPEC is assembled to simulate this framework and is actually applied to an SGTR sequence, and the resultant simulated behaviors of operator are obtained.

1. Introduction

As uses of nuclear power plant(NPP) automation have increased, the operator's role has become mainly of supervisor of automatic operations, carried out by pre-programmed computerized systems and of executor of well-established procedures.[1] As a consequence, the complexity of the control system and the tasks assigned to the operator make his activity particularly difficult and highly demanding in terms of skill and ability, every time his direct intervention is expected on the control of the plant.[2] It is therefore quite predictable that, in such highly reliable systems with complex control dynamics and supervisory role for the operator, the contribution of the human error in an accident transient is becoming particularly apparent.[3]

The identification of human errors has firstly been approached in the frame of Probabilistic Risk Assessment(PRA) analysis by Swain and Guttman[4] in a behavioristic oriented perspective, i. e., decomposing the overall behavior of the operator in a sequence of different elementary acts or sub-tasks and assigning, to each of these, a certain probability of failure. These have been then to be combined in order to obtain the failure probability of a certain mission. This type of approach, although very efficient in terms of quantification, has been questioned by some authors, like Norman[5] and Reason,[6] mainly on the basis of psychological consideration, implying that in a behavioristic view, only the consequences of human errors are accounted for, without worrying about the reasons and the underlying mechanisms of these errors.

Human errors are, by nature, common cause failures events and, if the external or motor behaviour of an operator can be described as a sequence of different elementary acts or sub-tasks, this composition makes little sense from a psychological viewpoint: the sequence of actions is the result of a previously developed planning process, which in turn is the consequence of a diagnosis of the situation.[7] This implies that the operator primary intentions and his different internal representations of the system, in terms of structural and functional schema, have to be taken into consideration at the same level of his behavioristic external performances in order to evaluate the overall process of decision-action performed by an operator of any plant or system.

These criticisms on the behavioristic approach and the recognised importance of the role of the human being, in managing transients and unexpected events, have boosted the research in the field of modeling the performance of operators, accounting for cognitive as well as motor activities and combining psychological consideration, logic formalism and decision making theories. There are several models based on the cognitive approach such as, CES,[8,9] GEMS,[10] INTEROPS,[11] and COSIMO,[12,13] and so on. These models are basically constructed based upon the concept of three categories of human cognition; skill, rule, and knowledge-based behaviors.[14] And it is found that even though each model has its own emphasis in modeling cognitive activities, all the existing models use the four-stage process ; monitoring, situation assessment, planning and execution. These models have to be considered a step forwards, in that they attempt to model the behavior of operators in a deterministic way, as it is done, in the case of plant analysis, with the simulation of the physical phenomena evolving within the system.

The cognitive approach certainly treats the facts which cannot be explicitly modeled in the behavioral approach. It is found that there are several elements which are not appropriately treated by any of existing models based on the cognitive approach. For example, all models treat individuals in a limited context ; they treat only individual responses without considering the communication between operators and its impacts on one's behaviour. Thus, in this paper, a more systematic cognitive model will be proposed as a basic tool for the detailed analysis of the human-machine systems in complex environments, like the control rooms of NPP.

2. Conceptual operator model

2.1 Requirements

During an emergency situation, an operator confronts with a series of dynamic situations, for example, through monitoring and manipulating the control board, he should interact with the plant which is fast and/or unpredictably varying over the time. In modeling the required operator cognitive behavior, not only the operator behavior itself but also his inter actions with the plant and with the other operators should be considered. The requirements for modeling are as follows : [1,15]

1. The operator model should be able to treat the changes which may develop as the accident evolves and the operator takes actions to return the plant to a desired state. The model should interact with the corresponding plant simulation, in order to handle the time-dependent aspects of man-machine interaction.
2. The operator model should be simple enough to cope with the plant simulation and to cover the variety and variability of human responses, which may be required for many different circumstances as analysed in a human reliability assessment(HRA) study.
3. This model should be capable of explicitly modeling the fact that the operating crew is composed of several different individual operators. And it should be able to handle interactions between individuals such as communications.
4. The operator model should be able to accommodate improvements over existing models without difficulty. This can be accomplished by

making the operator model modular.

Based upon the requirements, an integrated framework for control room operators' behaviors during an accident scenarios is shown in Figure 1. It incorporates a plant model and several individual models.

2.2 Plant Model

Plant physical variables are inputs to the operator models and may be altered by the evolution of plant condition itself and/or operator manipulation. To treat the interactions between operator and plant models, the interfaces between these two models should be explicitly represented. The plant model should be capable of providing with plant parameters including all alarms, and accommodating all operator actions that would affect the plant behavior.

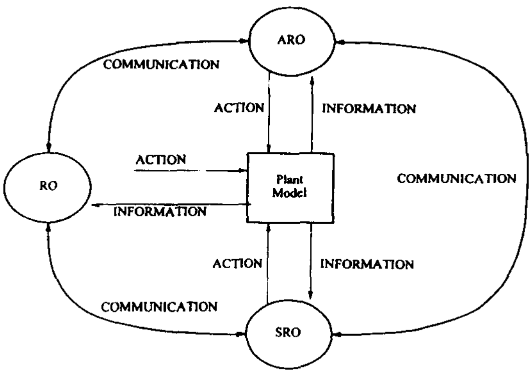

Fig. 1. Conceptual model for control room operators

2.3 Individual Model

As shown in Figure 2, the individual model consists of a cognitive process model as working space which performs cognitive activities and the memory system which supports cognitive process model. As for cognitive process model, four-stage model is employed, based upon the review of the existing models.

2.3.1 Memory System

In order to accomplish the cognitive activities, for

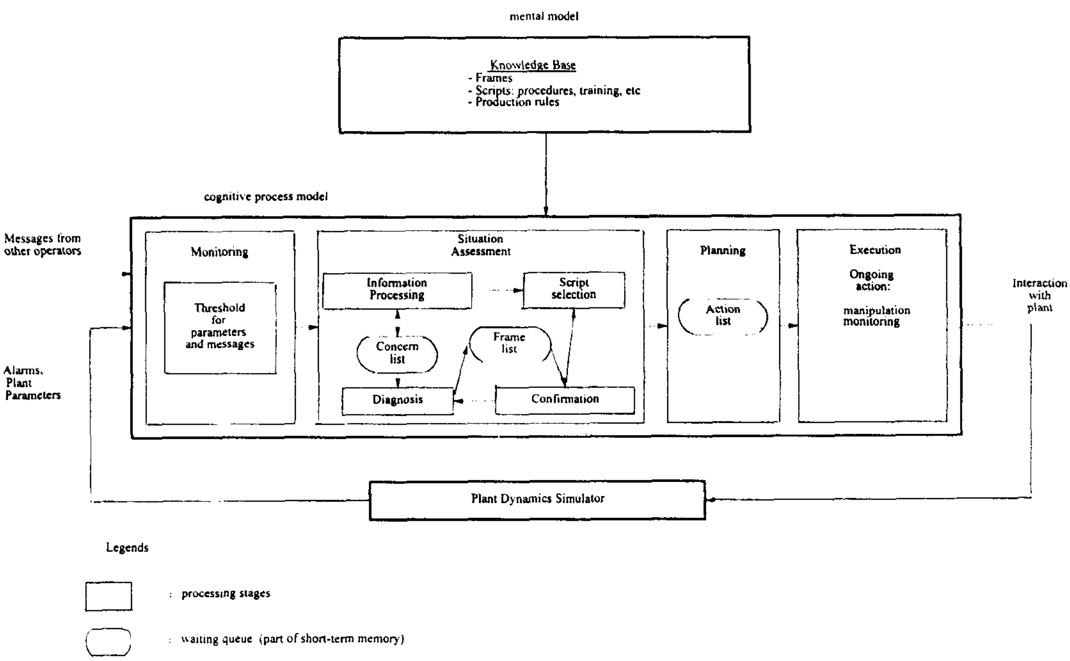

Fig. 2. Conceptual model for individual model

Table 1. Properties of long- and short-term memories

Feature	Short-term memory	Long-term memory
Capacity	Small	Not known limit
Information loss	Displacement Possibly decay	Possibly no loss
Trace duration	Up to 30 seconds	Minutes to years
Retrieval	Probably automatic Items in consciousness Temporal cues	Retrieval cues Possibly search process

example, reasoning or inference, demanded by a problem or a task, the operator needs to retrieve knowledges from his memory system. Studies in psychology[16,17] suggest two systems in retrieving knowledges. They are long- and short-term memory systems, which are normally interacting. The properties of two systems are summarized in Table 1.

For the short-term memory, two characteristics should be considered ; limitation of capacity and decay of contents. Regarding the limitation of capacity, a number of experimental studies have derived a magic number, the maximum number of items that a person can remember.[18] For the purpose of this study, the magic number of (7 ± 2) may be regarded as a good starting point to model the capacity of short-term memory. It should be noted that this number should be applied only to those items that can be recalled only from the short-term memory. Besides, the items stored in the memory can be forgotten and removed from the memory due to memory decay.

2.3.2 Cognitive Process Model

When faced with a problem, an operator has to solve the problem and return the plant to a desired state. Hence, the operator performs a series of cognitive activities. The task of trouble-shooting is usually the process of searching for a solution in the space consisting of one or more solutions and one or more non-solutions. The human cognitive behaviors associated with problem solving, which are also the basic assumptions of this work, are summarized[19~21] as follows :

1. In searching for the solution to a problem, operators naturally tend to rely on a pattern-matching, i. e, an automatic or nearly automatic process rather than laborious logical inference.
2. If the model should fail to recognize a familiar pattern, then it selects an action or solution using a laborious logical inference.

This kind of the pattern-matching oriented behavior is common in operators at a nuclear power plant. Therefore, the cognitive process model assumes that operators naturally tend to rely on pattern-matching, i. e., an automatic or nearly automatic process rather than laborious logical reasoning. And based upon the review of the existing models, it is assumed that the cognitive process associated with problem solving develops in four stages ; (1) monitoring, (2) situation assessment, (3) planning, and (4) execution.

2.4 Miscellaneous Factors

There are two elements which are not explicitly treated by any of existing models of cognitive approach. They are cognitive bias and stress. For the realistic simulation of human cognitive behavior, these two elements should be considered.

2.4.1 Cognitive Bias

The bias is a result of human cognitive heuristics. These heuristics are meta-level judgemental attitudes that humans are unaware of but that, nevertheless, influence their reasoning and judgement. In this context, the confirmation bias[11] and the availability bias[22] should be considered in constructing the operator cognitive model. The confirmation bias says that a human occasionally tends to stick with the first-found solution and to collect only the confirmatory information without considering other evidences. The availability bias says that in judging the relative frequency of occurrence of an event, humans take into account not only the probability of occurrence itself but also the intimacy of the event through various available information. The more available information about the event there is, the more the probability of occurrence is overestimated.

2.4.2 Stress

Stress buildup is generally recognized to affect an individuals' efficiency. Effects of stress on the operator cognitive behavior are well explained by Yerkes-Dodson law[23] which relates performance and arousal. The inverted U-shaped function suggests that, in a simple situation with few cues, stress will improve performance by causing attention to be focused, and in a complex situation with many cues, however, stress will decrease performance because many cues will go unattended. The overload also degrade performance, especially in the task that requires selection and execution of specific responses.[23] This sort of performance degradation may occur during an emergency operation at a nuclear power plant.

2.5 Interactions between individual operators

The importance of communication and its influence on group behavior have long been recognized by experts in the fields of social behavior science, civil aviation, and NPP operation. In an NPP control room, most group interactions occur through communications between operators. There are two types of communication ;[24] informational and verbal communication and emotional and non-informational communication. For ease of discussion, according to reference 15. these are denoted as task-related and non-task-related communication, respectively. Also, it is generalized that the failure of communication has occurred when :

1) the sender does not send out the message
2) the content of the message is distorted by the medium of the receiver's perception
3) the message is rejected by the receiver
4) the sender does not receive the appropriate feedback

3. Implementation of operator model

3.1 Plant Model

The thermal hydraulic codes which are currently available for the analysis of NPPs are too complex and time-consuming to be incorporated with the operator cognitive model. Thus, it is desirable to develop a simplified physical model, such as the linear regression model to correlate a physical variable with other related variables. The plant model used in this paper is obtained from Huang.[15] This model is for the analysis of steam generator tube rupture (SGTR) in a Westinghouse 3-loop pressurized water reactor (PWR).

An operator action that will affect the plant behavior is simulated by converting this action into a boundary condition, which governs the behavior of directly affected variables. For example, the operator action, start up the second charging pump, will change the status of charging pumps and hence increase the rate of charging flow. The effects of this operator action will relay to other physical variables, and these variables will be accordingly adjusted based on the updated value of charging flow. The failure of a system or component is treated in the same way as the operator action.

3.2 Memory System

The memory system is postulated by a knowledge base (KB), where the entire knowledge of the operator is contained. The frame,[25] script,[26] and production system[27] concepts are introduced to represent the KB. Considering the various cognitive processes, it seems reasonable that a combinatory form of three concepts is needed for its representation.

Regarding the frame, it is more suitable for pattern-matching diagnosis process. Therefore, the frames are constructed in the KB for pattern-matching diagnosis process. The construction of frames may be done by using basic concepts proposed by Cacciabue et al.[12,13] Each frame consists of the elements as follows (see Figure 3); (1) an index label identifying the type of accident, (2) a subjective frequency tag related to the number of times the operator has encountered this accident in the past, (3) a set of properties or attributes, and their associated attribute-values describing the symptoms expected and characterizing such an accident.

If the model should fail to recognize a familiar pattern using pattern-matching mechanism, then it selects an action or solution based on the use of a laborious logical reasoning. Hence, it is desirable to develop a production system, which has the basic form of "If A is true, then B is true," where A is the activating statement and B is the concluding statement. The example of production rules used in this study is shown in Table 2. Script is defined as a set of general rules or standard procedures used by operators in responding to a specific situation. This script is used in the script selection and planning stage. The example of scripts used in this study is shown in Table 3.

3.3 Cognitive Process Model

Following the initiating event in an accident scenario, the abnormal plant conditions challenge the operator with two major problems: What is the root cause? How can the plant be returned to a safe state? In responding to the first question, a diagnosis process is initiated to find the root cause. In parallel with the fault diagnosis process, a series of mitigative reactions are taken by the operator, to respond to the observed abnormalities and to bring the plant

SGTR	
Frequency: 0	
Symptoms	
Attribute	Attribute Value
PZR level deviation alarm	1
BOP radiation alarm	1
PZR level	(−)
Faulted SG level	(+)
2nd Radioactivity	(+)

Fig. 3. An example of frame structure

Table 2. An example of production rules for SGTR

Rule Name	IF A1 AND A2		Conclusion
	A1	A2	
P1	PZR level deviation alarm	PZR level still decreasing	Primary side leakage
P2	Primary side leakage	BOP radiation alarm	May be small LOCA
P2′	Primary side leakage	SG blowdown radiation high alarm	May be small LOCA
P3	Not small LOCA	May be SGTR	SGTR
P4	BOP radiation alarm	SG blowdown radiation high alarm	SG problem
P5	SG problem	SG mismatch	May be SGTR
P6	May be SGTR	Primary side leakage	SGTR

Table 3. An example of scripts for SGTR

concern	scripts
PZR level deviation alarm	To monitor PZR level
PZR level still decreasing	To increase charging flow
	To isolate letdown flow
	To start up a second charging pump
PZR level still decreasing after start up a second CCP	To reduce reactor power
Secondary or balance of plant (BOP) radiation high alarm	To check the radiation monitor
SGTR	Calling the chemistry department to sample the SG water
	To check mismatches in SG feedwater flows and levels
PZR level approaches 14%	Trip reactor

back to a safe state. These two major processes can interact with each other during the evolution of the accident scenario. For example, the results generated through the diagnosis process may serve to trigger mitigative reactions in the same way that an abnormality observed in a plant parameter would. On the other hand, the observed abnormalities, with or without mitigative reactions having been taken, may provide information to the diagnosis process. The detailed mechanisms of these interactions will be discussed in the following sections.

3.3.1 Monitoring Stage

At the monitoring stage, among a large number of plant parameters produced by the control board display, those which are actually perceived by the operator are selected or filtered. Regarding this, we need to pay attention to two issues. The first one is that not all information available from the control board displays can be observed by an operator. The second is the narrowing of field of attention, which has been identified as a commonly observed phenomenon in several cognitive models. The phenomenon is particularly important when an operator is under high stress or heavy workload.

For the first issue, the possibility of observing a given plant parameter is dependent on the physical and cognitive salience of the parameter perceived by the operator. The physical salience of a plant parameter depends not only on the nature of the parameter but also on the evolution of the accident scenario. The cognitive salience is also dependent on the evolution of the scenario, as well as his nature bias on plant parameters. This phenomenon is implemented by assigning a priority which reflects both physical and cognitive salience to each plant parameter and a filter threshold for each operator. And then, it is assumed that an operator will only monitor those parameters with priorities higher than the filter threshold, and that he will start from the one with the highest priority. For the second issue, it is treated by varying the filter threshold. Therefore, his threshold is increased by the incremental stress level or workload. The increased threshold will then decrease the possibility for an operator to observe parameters with low priorities.

3.3.2 Situation Assessment Stage

The function of this stage is to assess the plant parameters that pass the monitoring stage and generate appropriate responses. When the situation represented by the information is familiar to the operator, that is, if he finds the state information to match the attributes of stored knowledge structure, or, frame, the problem solving proceeds on that basis(rule-based behavior). For unfamiliar situations, that is, if an appropriate frame is not in his repertory, more laborious logical reasoning may be required. The function of this stage is represented by four substages; information processing, diagnosis, confirmation, and script selection.

3.3.2.1. Information Processing

Once a parameter passes the monitoring stage, information processing stage starts. This stage consists of two substages; concern generation and concern merge. The function of concern generation substage is to decide whether an input should become a concern, which is defined as an issue that should be dealt with by the operator. For a plant physical variable, questions such as "Is the status of the parameter expected?" or "Does the value of the parameter approach or exceed the tolerance limit?" are used to resolve this issue. The concern generated is then stored in the concern list.

The concern generated in the concern generation substage is then sent to the next substage, concern merge. The function of this substage is to merge those concerns that are related to the same system or issue. Whenever the concern merge substage receives a new concern from the concern generation substage, it searches for concerns in the concern list that are related to the new concern. If related concerns are found, then this new concern merges into the existing concern. Otherwise, the related concern will be generated and filed in the concern list. Note that the priority of the existing concern will increase as more new concerns merge into it. Prioritization of tasks to be executed, or, scheduling is a common human cog nitive activity. This is because each operator has limited processing resources and many processing activities are competing for these resources. The concern list is the first queue to simulate the competition among processing activities. The concern processed in this stage is used in diagnose stage and in script selection stage.

3.3.2.2. Diagnosis

Once the concern with the highest priority is passed to the diagnosis step, then, the accessibility to a frame is determined. That is based on the fact that, in order to utilize the knowledge structure in a judgemental situation, it should not only be available in the operator's long-term memory but also be accessible. A recent research[28] suggests that the accessibility is determined by frequency as well as recency of activation. In most realistic situations, however, it is not always easy to make crisp assessments of the accessibility of a given knowledge. Further, from a human problem solving point of view, the accessibility is not simple binary-valued attribute. Since the difficulty of crisply assessing this attribute may be avoided with the use of fuzzy set, we propose the membership function of accessibility to the particular frame.

Let $UR_i(t-T_i)$ be defined as the membership of frame i in the fuzzy set of accessed frames at time t, given that frame i was last used at time T_i. When a frame has recently been used, that is, $t-T_i$ not too large, it should be very easy to access. For some period of time thereafter the frame should continue to be perfectly accessed until some point at which it will begin to fade slowly from memory. The frame that has been used many times will probably fade from memory more slowly than the frame that has been used infrequently. Also, the availability cognitive bias should be considered. Thus, membership in the set of frames might be calculated by

$$UR_i(t-T_i) = \begin{cases} 1 & \text{for small } t-T_i \\ e^{-r(t-T_i)/(n_i+UB_i+1)} & \text{otherwise} \end{cases} \tag{1}$$

where

UR_i = membership of frame i in the set of frames,
t = current time,
T_i = time at which frame i was last used,
r = rate at which frame is forgotten,
n_i = number of times that frame i has been used, and
UB_i = availability bias measure, which will be discussed in section 3.5.1 in detail.

Then, it is assumed that the frames, which are associated with the concern and are satisfying the requirement, for example, in this paper $UR_i(t-T_i)$ is larger than the given threshold, are activated. Then the frames activated are stored in the frame list. A frame is selected in the activated or accessed frames and brought into play for further cognitive processing, by using two basic mechanisms; similarity matching (SM) and frequency gambling (FG), which represent the parallel, rapid and efficient component of the retrieval process. For the selection of the frame which is considered to best characterize the current state using SM mechanism, a single measure is needed, which represents the degree of matching between current state and the activated frame. Hence, the similarity measure is introduced.

Let a_i and b_i be the elements of A and B frames, respectively. The similarity measure, $S_{A,B}$ of A and B is defined by:

$$S_{A,B} = 1 - \frac{\sum_i |a_i - b_i|}{\sum_i (a_i + b_i)}$$

or equivalently by,

$$S_{A,B} = 1 - \frac{\sum_i |a_i \vee b_i - a_i \wedge b_i|}{\sum_i (a_i + b_i)} \tag{2}$$

where $\wedge$ and $\vee$ are binary operators which are defined respectivley as follows ;

$$a \vee b = \begin{cases} a \text{ if } a \geq b \\ b \text{ if } a \leq b \end{cases}$$

$$a \wedge b = \begin{cases} b \text{ if } a \geq b \\ a \text{ if } a \leq b \end{cases}$$

The similarity measure has the following properties ;

$$S_{A,B} = S_{B,A} \quad (3)$$

$$A = B \Leftrightarrow S_{A,B} = 1 \quad (4)$$

$$A \wedge B = 0 \Leftrightarrow S_{A,B} = 0 \quad (5)$$

SM is the comparison of the attributes of current state with the ones of the reference frame, that is, the one which characterizes the typical accident. Hence, the attributes of current state are compared with the ones of activated frames one by one. Then, using equation (2), the similarity measure is calculated. Finally the frame which have the maximum similarity measure is selected as the one characterizing the current state. In case of ambiguity, either in the interpreted data or in the attributes represented in the KB, more than one explicating frame may be brought to mind by the SM. The FG resolves the conflict between partially matched frames in favor of the more frequent one encountered in the past. The problem solving based on the SM-FG primitives is defined as an immediate information processing in contrast with a logical reasoning process.

3.3.2.3. Confirmation

Once a frame is selected in the diagnosis stage, the confirmation substage is initiated according to the attributes that better qualify the selected frame. The confirmation is made on the basis of the symptoms, which characterize the frame selected but not yet observed. The symptoms which are confirmed first are those with the highest diagnosticity, which represent the content of information of a cue with respect to the set of frames contained in the KB. Confirmed and unconfirmed symptoms are progressively added to the initial set of perceived cues, until the confirmation has attained a certain level of satisfaction. Incoherence between symptoms checked in the environment and symptoms of a specific accident provokes the reiteration of the diagnosis activity.

3.3.2.4. Script Selection

In the script selection substage, based on the concern which is generated in information processing stage, the operator may conclude whether the problem solving situation is familiar, and the appropriate script can be employed. If no script is available, the operator must use the structural information to plan in terms of generating alternatives, imagining consequences, valuing consequences, and so on.

3.3.2.5. Logical Reasoning

The logical reasoning is ancillary to pattern-matching mechanism if SM and FG mechanisms should fail to search the root cause of an accident sequence. Hence, if SM and FG fail to select the appropriate frame characterizing the current state, the logical reasoning is used to generate concerns relevant to the current state. These concerns are stored in the concern list and processed in the same way as previously described. This requires the structured knowledge from the KB and evidence from the concern list.

For logical reasoning, a concern is first compared with the production rules to see whether it appears as the first item in the activator statement of any production rules. If none of the production rules is applicable to this concern, then the logical reasoning is terminated ; if a rule is found, the next step is to seek the corresponding evidence in the concern list. When corresponding evidence is not found on the concern list, the operator may passively wait for the arrival of the corresponding evidence or actively generate a new concern to collect information about corresponding evidence. The newly generated concern,

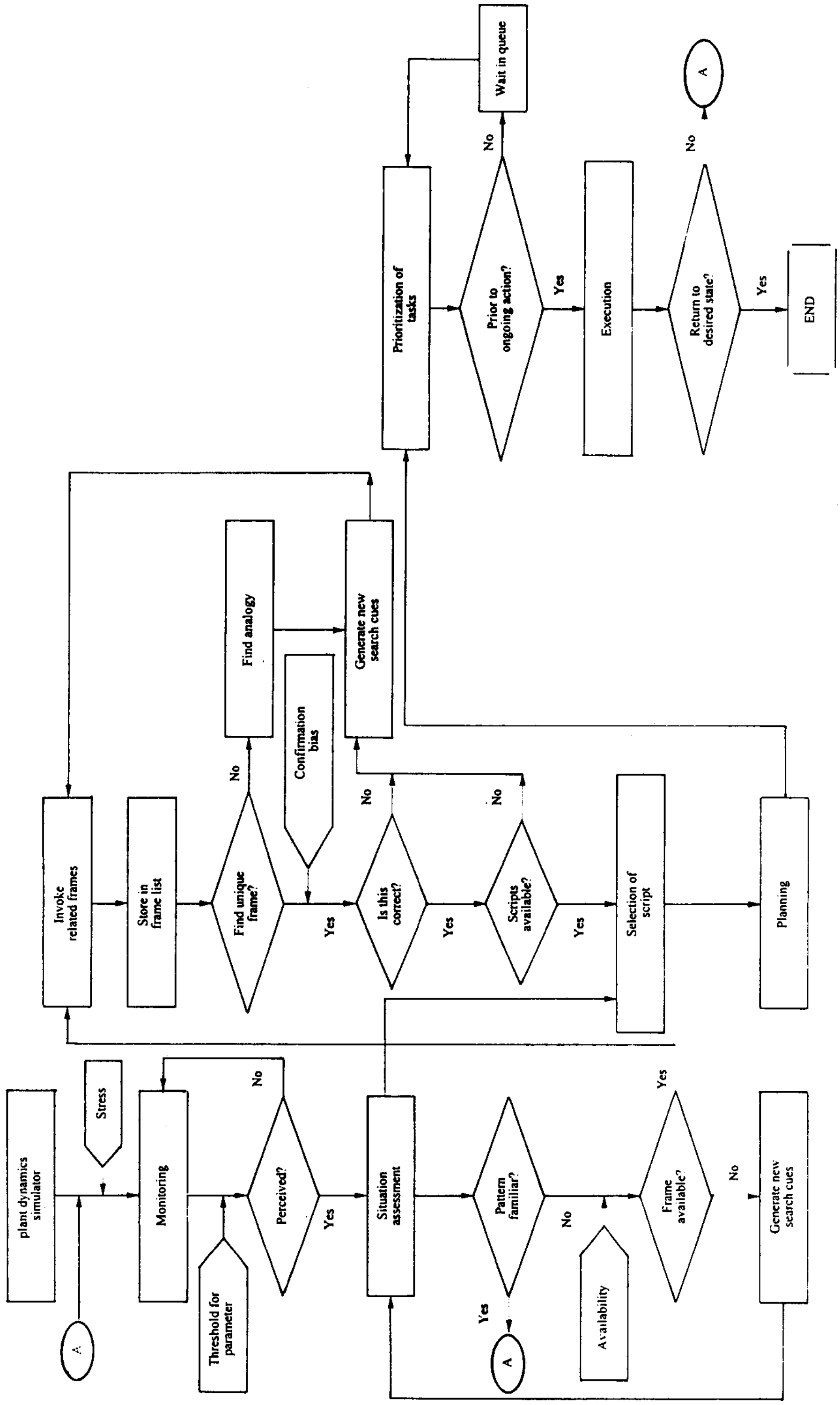

Fig. 4. Flow diagram of individual model implemented

the conclusion, is an input to the concern merge substage, after which it is filed in the concern list for further processing.

3.3.3 Planning Stage

The planning stage receives the actions in script generated by the previous script selection substage and arranges these actions according to their priorities for future execution. As previously mentioned, the prioritization of tasks for execution is a common cognitive activity due to limited processing resources. Hence, the queue is needed to simulate the competition among processing activities. With the priorities subjectively assigned to each action by the operator, the actions waiting for execution are temporarily stored in this queue. Whenever the contents of the queue have been changed either by addition of new action or by modification of the priority of any action previously existing in the queue, a competition for available resources begins. The priority of each action waiting in the queue is compared with that of the current execution action. If the priority of the action is higher than that of the ongoing action, the possibility of interrupting the ongoing action is high : otherwise, the action is more likely to wait in the queue until the resource is available, that is, until the ongoing action is completed.

3.3.4 Execution Stage

The action, chosen as the ongoing one, is then executed in the execution stage. The actions generated and executed are categorized into either manipulation or monitoring. While executing either manipulation or monitoring actions, operators have to interact with the plant. These actions may generate the feedback to or acquire the information from the plant. After the execution of an action, the operator will rearrange the contents of his frame, concern and action lists, and pick the first action in the action list for execution.

The flow diagram of the four-stage cognitive processes is shown in Figure 4.

3.4 Interactions

3.4.1 Interactions of operator with plant

The plant model discussed in Section 3.1 is capable of generating alarms, of providing updated plant parameters, and of accommodating the effects of predefined operator actions. The concept of discrete event simulation, i. e., everything that occurs during a short time interval is assumed to occur at the end of this interval, has been adopted to simulate the plant behavior. The time interval duration is judged to be appropriate for the slowly evolving SGTR sequence, but can be easily changed to accommodate faster transients. The first type of interaction between an operator and the plant is the monitoring (information retrieval) process. The second type of interaction is operator's manipulations of the control switches.

3.4.2 Interactions between operators

As mentioned in Section 2.5, task-related communication can be simulated by explicit treatment of the contents of each message and by considering failures related to the communication process. Also considered is the time delay in sending out message, which occurs when the receiver is occupied. On the other hand, non-task-related communication is somewhat more ambiguous and unpredictable. For this, Huang model[15] is employed which assign a tone to each emitted message.

3.5 Miscellaneous Factors

3.5.1 Cognitive Bias

The confirmation bias may be implemented by introducing a cognitive filter in the confirmation substage. The bias is applied only if the diagnostic value of contradictory evidence exceeds the filter threshold. And then a new searching process starts.

The availability bias will have influence on the cognitive process which needs the judgement. Therefore, in this paper, it is assumed that this bias have only influence on the diagnosis. For quantification of this bias, the concept of availability measure factor, δ, is introduced along with the occurrence frequency of an event. Let availability measure factor, δ, be defined as the degree to which an operator is affected by the information obtained in the past. For example, if an operator is more affected by the information in the past, the availability measure factor is taken as a large value. Otherwise, the value is small. Therefore, the availability bias might be quantified by the equation

$$UB_i = 1 - e^{-\delta_i \times n_i} \tag{6}$$

where

UB_i = availability measure of an event,

δ_i = availability measure factor of an operator

n_i = frequency of an event encountered in the past.

3.5.2 Stress

For quantification of stress effects, this model uses a highly simplified approach to treat stress buildup and its effects on individual and crew behavior. In this approach, an operator's stress consists of an initial value of stress and two dynamic stress components : burden and irritation. This can be expressed by the equation ;

$$S_{total} = \sum_{i=1}^{2} S_i(t) + S_0 \tag{7}$$

where

S_{total} = total stress at time t,

S_i = stress value of component i at time t, and

S_0 = initial stress value assigned to operator.

The burden stress represents the stress arising from an operator's workload. The irritation stress results from interactions with other operators.

The accumulated stress will affect an operator's behavior and subsequently influence the effects on the individual characteristics such as filter threshold, time factor, etc. Therefore, it is assumed that an operator's filter threshold and time factor change with respect to his stress level. The initial stress value represents the operator's stress at the beginning of an accident sequence, that is, at the time the first abnormality is detected.

4. Case study

Based on the discussions in section 3, a simulation code, OPEC(OPErator Cognitive simulation code), is prepared. This code is implemented in a C++ language. To assess whether OPEC plausibly describes the operator cognitive behaviors during an accident situation, OPEC is applied to the steam generator tube rupture (SGTR) event without any additional hardware failures. The simulation starts from the pressurizer level deviation alarm or BOP radiation alarm, and ends when the reactor trip is executed. The total simulation time is 4 to 5 minutes. For the purpose of comparison, the input data required for simulation are employed from [15] as possible.

The simulated behaviors for the two crews by OPEC are summarized and compared with the reference values[15] in Table 4. In summary, the OPEC has successfully demonstrated its capability in simulating almost all of the crew behavior which is presented in reference in the aspects of existences, ordering, and timing. It also shows its ability to explicitly model the interactions between operators.

The analysis of the result shows that there is a relationship between the technical ability of an operator, such as assessibilty to a frame, and his response to a specific cue. As shown in Table 4, the better the accessbility to frame is, the faster the diagnosis process and the action is executed. As a result, the performance of the team 2 is better than that of team 1.

To understand the implications of the proposed

Table 4. Summary of simulated behaviors and comparison of reference

	Team #1			Team #2		
Plant or team behaviors	sim.	obs.	ref.	sim.	obs.	ref.
BOP radiation alarm	0:00	0:00	0:00	2:33	2:45	2:33
SRO commands ARO to check radiation monitor	0:16	N/A	0:19	N/A	N/A	N/A
PZR level deviation alarm	0:36	0:35	0:51	0:00	0:00	0:00
SRO check radiation monitor	N/A	N/A	N/A	2:50	2:50	2:48
ARO proactively report PZR and SG status	Yes	Yes	Yes	No	No	No
SRO : start 2nd centrifugal charging pump(CCP)	1:43	N/A	N/A	0:50	1:20	0:45
RO suggests "start 2nd CCP"	N/A	N/A	N/A	N/A	N/A	N/A
SRO : reduce power	N/A	N/A	N/A	1:27	2:00	0:48
RO suggests "power reduction"	2:48	2:45	2:50	N/A	N/A	N/A
SRO concludes SGTR	4:13	2:55	3:18	3:44	3:00	3:24
RO suggests "trip reactor"	4:43	4:46 5:15	5:05 5:25	N/A	N/A	N/A
Trip reactor	5:15	5:30	5:58	4:16	4:10	3:51

1. sim. : simulated behavior
2. obs. : observed behavior
3. ref. : behavior in reference
4. all time in minute : second

Table 5. Summary of sensitivity analysis for burden stress

Burden Factor: SRO/RO/ARO	Irritation Factor: SRO/RO/SRO	Conclusion SGTR min.:sec	trip Rx min.:sec
all 0.1	all 0.001	3:45	4:20
all 0.2	all 0.001	3:47	4:25
all 0.3	all 0.001	3:51	4:31
all 0.4	all 0.001	3:52	4:35
all 0.5	all 0.001	3:57	4:41
all 0.6	all 0.001	3:58	4:44
all 0.7	all 0.001	4:00	4:48
all 0.8	all 0.001	4:02	4:50
all 0.9	all 0.001	4:04	4:53
all 1.0	all 0.001	4:07	4:59

Table 6. Summary of sensitivity analysis for burden and irritation stress

Burden Factor : SRO/RO/ARO	Irritation Factor : SRO/RO/SRO	Conclusion SGTR min. : sec	trip Rx min. : sec
all 0.1	all 0.1	3:46	4:20
all 0.2	all 0.2	3:49	4:27
all 0.3	all 0.3	3:55	4:37
all 0.4	all 0.4	4:03	4:50
all 0.5	all 0.5	4:14	5:06
all 0.6	all 0.6	4:29	5:26
all 0.7	all 0.7	4:56	6:02
all 0.8	all 0.8	5:23	6:44

model for stress, the coefficients representing each operator's sensitivity to two sources of stress modeled are varied. Corresponding to these are two coefficients; the burden factor and irritation factors. The sensitivity analysis results are presented in Table 5, 6. According to sensitivity study, it is found that burden stress is recognized to affect an individual's and team's performance and irritation stress has little impact on the team's performance. However, as shown in Table 6, in case irritation stress increases together with burden stress, the team performance degradation is noticeable.

5. Discussion and conclusion

This paper proposes an integrated framework of modeling human operator behaviors during nuclear power plant accident scenarios. It incorporates both plant and operator models. The plant model continuously provides an individual operator with the information in the form of plant parameters and receives the feedback from the operator to update the plant status. The operator model processes the inputs from the plant and then generates outputs such as manipulation and/or monitoring. The basic structure of the operator model is similar to those of existing cognitive models. The model used in OPEC differs from those cognitive models largely in two aspects. First, using frame and membership function, the pattern matching behavior, which is identified as the dominant cognitive process of operators responding to an accident sequence, is explicitly implemented in this model. Second, the non-task-related human cognitive activities like effects of stress and cognitive biases such as confirmation bias and availability bias, are also considered. This model is applied to an SGTR sequence, and then the simulated behaviors of operator are obtained.

Through this work, we identified a number of important factors affecting operator performance additional to existing models. These factors are, however, implemented in the model rather deterministically, which needs further improvements for PSA application.

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