Design of an Integrated Operator Support System for Advanced NPP MCRs: Issues and Perspectives

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Abstract

Recently, human error has been highlighted as one of the main causes of accidents in nuclear power plants (NPPs). In order to prevent human errors during the main control room (MCR) operations, which are highly complex and mentally taxing activities, improved interfaces and operator support systems have been developed for advanced MCRs. Although operator support systems have the capability to improve the safety and reliability of an NPP, inappropriate designs can have adverse effects on the system safety. Designs based on systematic development frames and validation/verification of the systems are pivotal strategies to circumvent the negative effects of operator support systems. In this paper, an integrated operator support system designed to aid the cognitive activities of operators as well as theoretical and experimental evaluation methods of operator support systems are reviewed. From this review, it was concluded that not only issues about systems (e.g., the accuracy of the system outputs),but also issues about human operators who use the systems (for instance, information quality, the operator's trust and dependency on support systems) should be considered in the design of efficient operator support systems.

Keywords

Advanced main control room • Decision support system • Operator support system

2.1 Introduction

A nuclear power plant (NPP) is operated by operators in a main control room (MCR). Usually, the operators in an MCR consist of three to five operators and the number of operators is different according to the plant type. The operators always monitor the plant status and manipulate the control devices when necessary. The MCR operators perform a supervisory role of information gathering, planning, and decision making, which are complex and mentally taxing activities.

In safety-critical and complex systems such as NPPs, human error could be a serious cause of accidents because of complex interfaces, task-loads, lots of information, dynamic situations, and so on. In fact, after the TMI accident, human error in NPPs has been a considerable concern. In an analysis of the abstracts from 180 significant events reported to have occurred in the United States, it was found that 48 % of the incidents were attributable to human-factor failures [1]. There have been two approaches to prevent human error during MCR operations. The first approach is the provision of better training and education programs for operators. The second is to improve human machine interfaces (HMIs) with improved interfaces and operator support systems.

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Fig. 2.1 The advanced MCR in APR1400 [4]

Recently, the MCR interfaces have been considerably changed by adapting modern techniques. As the processing and information presentation capabilities of modern computers increase, the trend is shifting toward the application of modern computer techniques to the design of advanced MCRs [2]. The design of instrumentation and control (I&C) systems for various plant systems is rapidly moving toward full digitalization, with an increased proportion of automation [3].

As shown in Fig. 2.1 [4], advanced MCRs (modernized MCRs) have been considerably simplified, and now use large display panels (LDPs) and LCD displays instead of analogue indicators, hand switches, and alarm tiles. In this MCR, operators do not have to move around the room in order to view indicators or even control devices. Every necessary action is handled in their position. Moreover, many pursuits have been made to develop operator support systems that allow more convenient MCR operation and maintenance.

The operator support systems aim to provide useful information to operators for optimizing the workload of operators and convenient operation environment. However, they could cause not only positive effects but also negative effects on the system safety. Since operator support systems could directly affect the decisions of an operator, their effects should be evaluated carefully. The new systems could reduce the possibilities of some human errors, but new types of human errors could occur or possibilities of some human errors could increase.

Inappropriate design of an operator support system may cause the confusion of operators by providing unnecessary or inaccurate information. In order to prevent negative effects, systematic development frames and evaluation methods for operator support systems are necessary. In this paper, three papers about the design of the integrated operator support system [5] and the evaluation of the operator support systems [6, 7] were reviewed and issues and perspectives for designing the effective operator support systems were discussed.

2.2 Operator Support Systems

2.2.1 What Are Operator Support Systems?

The operators in an MCR are under high workload situations due to task load, dynamic situation, and plenty of information for operating and maintaining an NPP. Operator support systems represent the systems which provide useful information to operators or automated systems for preventing human errors. They aid in improving operator performance by pre-processing the raw data, interpreting the plant state, prioritizing goals, and providing advice. They also help the operator focus attention on the most relevant data and the highest priority problems, as well as dynamically adapt the proposed response plans to changing situations. Computerized support of operational performance is needed to assist the operator, particularly in coping with plant anomalies, so that any failures of complex dynamic processes can be managed as quickly as possible with minimal adverse consequences [3].

The roles of an HMI and operator support systems are briefly shown in Fig. 2.2: the left diagram shows the independent operator support systems used in conventional MCRs, and the diagram on the right shows an HMI, including

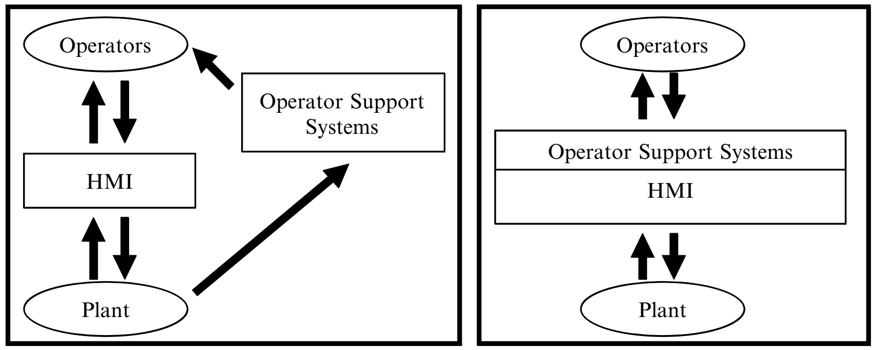

Fig. 2.2 Independent and included operator support systems

the operator support systems, that perform the role of an agent for advanced MCRs.

In conventional MCRs which are not computer-based systems, operator support systems are used as independent systems to provide additional information to augment MCR design data. Operators can operate a plant without the information of support systems. Owing to the fact that such information may increase the amount of information which should be managed by an operator, it is not easy to consider the information for operators during complex situations, especially in emergency situations, even though the information is vitally useful.

The operator support systems can be included as part of an HMI of advanced MCRs which are computer-based systems. Such included support systems provide useful information to operators by abstracting, filtering, and integrating the raw data of a plant, so that the amount of information and the workload could be reduced. It may be more efficient to combine the HMI and support systems into one system.

There are various kinds of support systems at work for NPP operators, aiding with surveillance, diagnostics, and the prevention of human error. Some of these, such as early fault detection systems [8], are capable of doing tasks which are difficult for operators. Others, such as operation validation systems, are intended to prevent human errors [9]. As MCRs evolve, more support systems will be adapted. However, according to the results of several published support system evaluations, a support system does not guarantee an increase in operator performance [10] and inappropriate operator support systems or automation systems can cause adverse effects [11]. Some support systems could degrade an operator's situational awareness capability and may increase an operator's mental workload.

When an automated system or support system fails to respond correctly, an operator who detects that failure should be able to supersede the system's decision. Considering the operator's oversight role in such cases, authority for some tasks should be retained by the operator. This problem is called "out-of-the-loop unfamiliarity" [12], and when it occurs, an automated system or support system that cannot manage a particular problem could degrade a human operator's performance [13].

According to research from the OECD Halden Reactor Project, as the automation level of an advanced MCR is increased, the concept of human-centered automation should be considered for more efficient automation [14]. In addition, a moderate level of automation that provides decision support while retaining human control of the final decision is optimal in the quest for maintaining operator situation awareness [15].

A fully automated system could be more efficient for some tasks, while a support system could be more efficient for others. Simple tasks could be managed more efficiently by automation. In contrast, a support system could be more efficient at managing complex tasks that operators would need to comprehend and analyze, because high levels of automation may reduce operator awareness of system dynamics. MCR operators in particular must be aware of and comprehend a given situation correctly in real time, thus they should be the final decision-makers. In view of this, support systems may be more appropriate than highly automated systems for operators in MCRs.

2.2.2 Human Cognitive Process Model of MCR Operators

The authors proposed an integrated operator support system to aid the cognitive activities of operators (INDESCO: Integrated Decision Support System to Aid Cognitive Activities of Operators) as one of the design frames for efficient operator support systems. It was designed with the consideration of human aspects to generate more convenient information to support operators and avoid human errors.

The objective of INDESCO is to offer an integrated operator support system for operators of advanced HMIs by suggesting operator support systems based on the human cognitive process. An operator's operation processes are analyzed with respect to the human cognitive process, and systems that support each cognitive process activity are suggested.

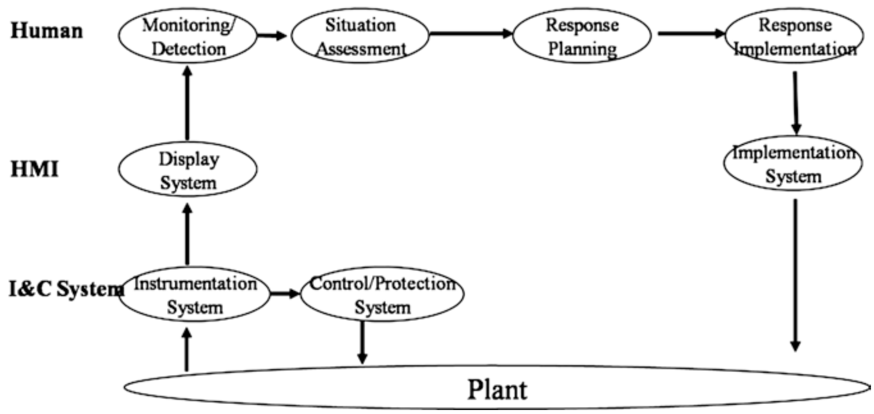

Fig. 2.3 NPP operator's operation process [13]

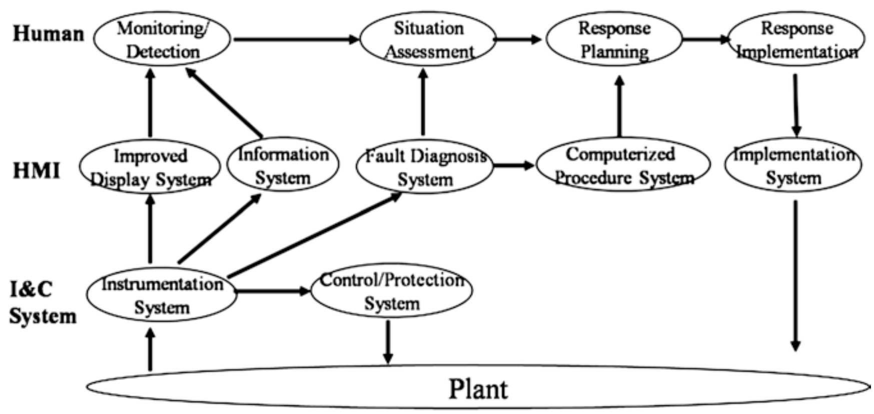

Fig. 2.4 NPP operation process with operator support systems

INDESCO performs processes similar to the cognitive processes of operators in order to detect and prevent human errors which can occur during the cognitive process. INDESCO is proposed based on the cognitive activities for NPP operations underlying a technique for human error analysis (ATHEANA) [16, 17].

The major cognitive activities for NPP operations underlying ATHEANA are: (1) monitoring and detection, (2) situation assessment, (3) response planning, and (4) response implementation. These activities can be further described as follows [17]:

1. Monitoring and detection: This refers to the activities involved in extracting information from the environment.
2. Situation assessment: When confronted with indications of an abnormal occurrence, humans actively try to construct a coherent, logical explanation to account for their observations. This process is what is referred to as situation assessment.
3. Response planning: This refers to the process of making decisions about what actions to take. In most cases in NPPs, when written procedures are available and deemed appropriate to the current situation, the need to generate a response plan in real time may be essentially eliminated. However, operators still need to (1) identify appropriate goals based on their own situation assessment, (2) select the appropriate procedure, (3) evaluate whether the procedure-defined actions are sufficient to achieve those goals, and (4) adapt the procedure to the current situation as necessary.
4. Response implementation: This refers to taking the specific control actions required to perform a task. It may involve taking discrete actions or continuous control actions.

Figure 2.3 shows the relationship existing among a human, an HMI, I&C systems, and a plant [18]. All HMIs in MCRs have display and implementation systems for monitoring and controlling the plant. Human operators obtain plant information through the display system in the HMI layer and assess the current situation using the obtained information. In the following step, the human operators select the operations corresponding to the assessed situation. Finally, they implement the operations using the implementation systems. According to a task, only several cognitive activities may be used or some cognitive activities may be used repeatedly. More detailed cognitive activities may also be necessary in order to analyze some tasks. However, almost all operation tasks of MCR operators could be represented using these four cognitive activities.

Operator support systems aid the cognitive activities of operators as shown in Fig. 2.4. Operators can perceive the plant status more easily and quickly using the information provided by the improved display system, as well as obtain digested data from the information system. The fault diagnosis system assists and supports operator situation assessment tasks, therefore it can improve the situation assessment activities in the operator's cognitive process. In the same way, response planning activities can be supported by the computerized procedure system (CPS).

Even if the design and components of a HMI are changed, the relationship among an operator, a HMI, I&C systems, and a plant can be represented using this model. The model shows which cognitive activity an added support system relates to and supports. Support systems necessary to support specific cognitive activities can be suggested and selected based on this model.

2.2.3 Operator Support Systems for Cognitive Processes

Various operator support systems can be added to the HMIs to support cognitive process activities. Among these systems, the most appropriate support systems can be selected based on the cognitive process, thus enhancing operational efficiency. The features of operator support systems which aid each cognitive activity are described as in the subsequent sections:

2.2.3.1 Support Systems for the Monitoring/Detection Activity

Monitoring/detection activities access a high volume of NPP information in order to detect abnormal situations. This activity is performed by instruments and alarms in MCRs. Operators always monitor the instruments and alarms in order to detect variation of instrument values or changes of color or the sounding of alarms. Upon detecting an abnormal situation, operators proceed to situation assessment.

In a NPP, there are many instruments that indicate the status of the plant. While an analysis of all instruments is the best way to ensure a correct detection and diagnosis, the sheer number of instruments makes it impossible for operators to examine each individually. If there is no alarm that serves as a major information source for detecting process deviations, operators have to consider a large number of instruments and an operation will take too long. A slow reaction on the part of the operator could result in accidents with serious consequences. Alarms help operators make quick detections by reducing the number of instruments that must be considered.

Though alarms are helpful in this way, there are a multitude of them; a typical MCR in an NPP has more than a thousand alarms. In emergency situations such as a loss of coolant accident (LOCA) or a steam generator tube rupture (SGTR), hundreds of lights turn on or off within the first minutes, and having many alarms that repeatedly turn on and off may cause operator confusion.

There are two approaches to support monitoring/detection activities. The first approach is to improve the interface of an MCR, and the second approach is the development of an advanced alarm system.

Advanced MCRs have been designed as fully digitalized and computer-based systems with LDP and computer displays. More efficient displays could be designed using these advanced displays, but there are several disadvantages. Using the LDP and computerized display system, a more flexible display design is possible. However, the plant information is provided to operators through computer screens in hierarchical forms due to spatial limits. Operators have to navigate screens in order to find the information they want, and excess NPP information increases the number of necessary navigations. If too many navigations are required to find a control or an indicator, the system becomes inefficient. Therefore, a key support for monitoring and detection activities is the efficient display of information.

An advanced alarm system also supports monitoring and detection activities. Conventional hard-wired alarm systems, characterized by one sensor-one indication, may confuse operators with avalanching alarms during plant transients. Conventional alarm systems possess several common problems, including the issues of too many nuisance alarms and that of annunciating too many conditions [19]. Advanced alarm systems feature general alarm processing functions such as categorization, filtering, suppression, and prioritization. Such systems also use different colors and sounds to represent alarm characteristics. These functions allow operators to focus on the most important alarms.

2.2.3.2 Support Systems for the Situation Assessment Activity

During situation assessment activities, operators analyze the situation at hand, make a situation model, and generate appropriate explanations for the situation. Systems which analyze the information representing that situation, and generate estimated faults and expected symptoms could be useful for supporting situation assessment activities; fault diagnosis systems and alarm analysis systems are typical examples. An alarm analysis system could be regarded as either a kind of fault diagnosis system or as a part of one, because they have equivalent objectives.

Operators make operation plans based on operating procedures which are categorized into two types: event-based procedures and symptom-based procedures. Different support systems should be assigned to situation assessment activities on the basis of these procedure types. In case of event-based procedures, operators start to execute procedural operations after identifying a situation. Thus fault diagnosis systems offering expected faults would be useful for quick and easy situation assessment.

However, operators using a symptom-based procedure do not begin by diagnosing a situation. Instead, they determine the appropriate procedure by comparing the procedure entry conditions with the current parameters, and then act according to the selected procedure. For operators using such a method, a system to suggest the appropriate procedure for a given situation would be more useful than a fault diagnosis system.

A critical issue for situation assessment activity support is the reliability of the support system. This is because, without a high degree of reliability, operators will distrust the support system. If operators must always consider the possibility of incorrect results, the support system will be rendered ineffective. Therefore, there have been researches employing knowledge bases, neural networks, genetic algorithms, and other means to develop more reliable fault diagnosis systems [20–22].

2.2.3.3 Support Systems for the Response Planning Activity

In general, response planning activities involve the operator's situation model of the plant state to identify goals, generate alternative response plans, evaluate response plans, and select the most appropriate response plan relevant to the situation model. However, one or more of these steps may be skipped or modified in a particular situation [17]. As aforementioned, when written operating procedures are available and judged appropriate to the situation, operators can handle the situation according to those procedures. In such cases, errors arising from omission of a step or selection of a wrong step are of particular concern. Written operating procedures are designed to avoid such errors, and procedures intended to avert emergent situations are designed with more stringent and formal linguistic formats. For example, NPP emergency operating procedures (EOPs) intended to handle most serious accidents mainly consists of IF-THEN-ELSE statements.

Though operators may be provided with well-written procedures, there is still the potential for human error. Since the content of the paper-based operating procedure is written in a fixed format in natural language, the information can sometimes be overwhelming, making it difficult to continuously manage the requisite steps.

Due to the deficiencies of paper-based operating procedures, CPSs have been being developed and implemented since the 1980s [23, 24]. In a CPS, information about procedures and steps, relations between the procedures and steps, and the parameters needed to operate the plant are displayed. Such systems also provide functions, such as check-off provisions and a compendium of candidate operations, to prevent operator errors such as omission of a step, or selecting a wrong step. For example, if operators confirm that an operation is performed using check-off provisions after each action, then the probability of omission errors may decrease.

2.2.3.4 Support Systems for the Response Implementation Activity

Response implementation activities are those activities which execute the selected operation after planning a response (e.g., flipping a switch or closing a valve). In this step, simple errors rather than decision-making errors are the concern. Operators can still commit an unsuitable operation despite correctly assessing a situation and making an appropriate plan. Accidents caused by such commission errors have in fact been reported.

Response implementation supports such as an operation validation system have been proposed to prevent such commission errors. The objective of an operation validation system is to detect inadequate operations and to warn operators about them, in order to allow a chance to double-check operations which pose the possibility of commission errors. One of the most important considerations in the design of an operation validation system is to optimize the system-initiated interruptions. Provided that operators follow operation rules and procedures, such a system should allow operators to perform tasks as they prefer [9]. Although a validation system should interrupt all operations which may go wrong, too many interruptions result in excessive operation validation time. Moreover, operators become accustomed to repeated interruptions, resulting in their becoming oblivious to them. If operators are always or frequently required to double-check their operations, then the double check loses its original significance. On the other hand, if a validation system has too liberal a validation filter, then it may also fail to accomplish its objective. Therefore, it is necessary to have an optimized interruptions from a validate operation system.

According to the functions in a support system, it could not be easy to define the cognitive activities which are supported by the system. For instance, a CPS usually supports the response planning activity because, basically, it is a computerized form of paper-based procedures, and operators make a plan using the procedures. However, additional functions are utilized in some CPSs, such as functions for providing the necessary information and guideline for planning. In this case, the CPS is regarded to support not only response planning activity, but also situation assessment activity.

2.2.4 Integrated Decision Support System to aid Cognitive Activities of Operators (INDESCO)

INDESCO is an integrated operator support system, which aids every activity of the human cognitive process model and integrates these support systems into one system

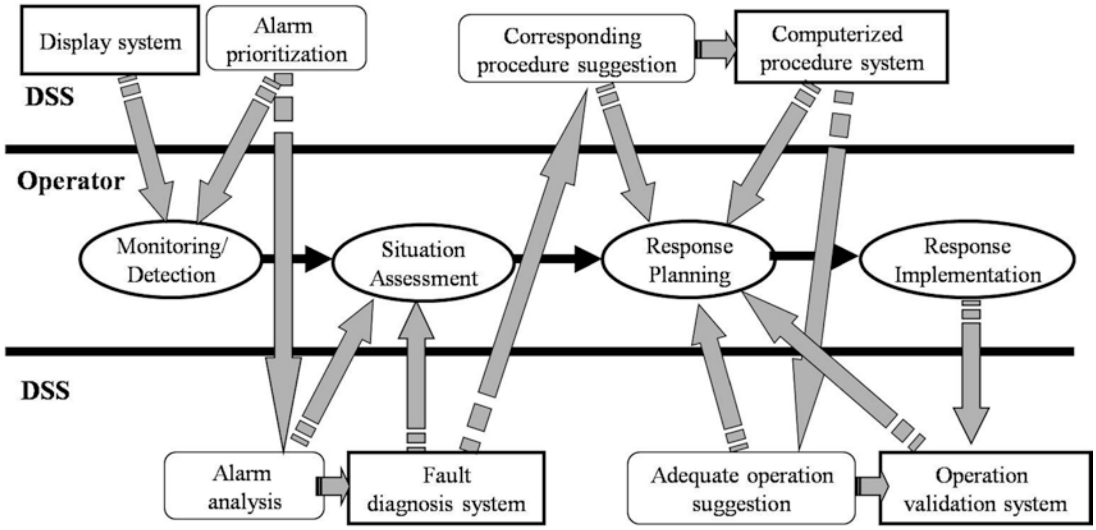

Fig. 2.5 The architecture of INDESCO

to maximize efficiency. That is to say, INDESCO is not a system that helps a task or supports a part of the cognitive process of an operator, but rather supports every major cognitive activity by integrating the support systems that support each cognitive activity.

The simple architecture of INDESCO prototype is shown in Fig. 2.5. A display system supports the monitoring and detection activities. A fault diagnosis system, a CPS, and an operation validation system support the other cognitive activities. In addition, there is an alarm prioritization system, an alarm analysis system, a corresponding procedure suggestion system, and an adequate operation suggestion system. Since the latter four systems can be implemented as subsystems of the former four systems, the former four systems are classified as the main support systems.

The system shown in Fig. 2.5 is a prototype of INDESCO. Recently, various kinds of operator support systems have been developed, so that useful support systems could be added or substituted for the systems in the prototype. Flexible designs are also possible according to the specific features of tasks (e.g. supporting an important cognitive activity with more support functions). The important thing is to balance supports of cognitive activities through the whole cognitive process.

2.3 How to Evaluate Operator Support Systems

It is very important to design highly reliable operator support systems in order to adapt them in actual NPPs. In addition, to evaluate those support systems and validate their efficiency and reliability is as important as to designing highly reliable operator support systems. There is abundant research regarding the evaluation of operator support systems for operators. These involve evaluations using various methodologies and factors. In theoretical research, various types of models have been delineated, such as the discrete function model [18], and the Bayesian Belief Network (BBN) [25]. In experimental studies, operator performance with operator support systems is estimated by the quality and accuracy of a diagnostic performance [26], the number of navigated windows and time spent for diagnosis, [10], and other subjective or objective measurements. The authors proposed theoretical and experimental evaluation methods for the operator support systems. BBN is used in the proposed theoretical evaluation model, and the operation accuracy and workload are used as measures in the experimental method.

2.3.1 Theoretical Evaluation Approach Using BBN Model

The proposed model is basically constructed using the BBN model for situation assessment of a human operator, which was developed by Kim and Seong [25, 27]. HRA event trees are used to define additional nodes and their relations pertaining to the operator support systems. Several performance shaping factors are considered in order to create a model that takes into consideration human operators. Operator expertise and operator stress level, are used as performance shaping factors. In this model, in order to observe the effects of operator support systems, the effects are estimated. In cases where no operator support system is used, one or two operator support systems are employed, and all the four operator support systems that aid complete cognitive activities are used. To perform the evaluations, several assumptions were made and two evaluation scenarios were selected.

2.3.1.1 Assumptions for Evaluations

For the evaluations, some conditions are assumed and several assumptions are made from the model developed by Kim and Seong [27]. Operator support systems such as the fault diagnosis system and operation validation system are still in development, and as such there are no human error probability (HEP) values for these entities.

The objective of this evaluation is not to analyze the impact of certain specific systems that have already been developed, but rather to estimate the effect of the operator support system supporting the cognitive activities. Therefore, values of several parameters pertaining to operator support systems are assumed in this work. Assumptions are described as follows (detailed assumptions are described in the author's paper [6]):

1. For simplicity, only four representative states of the plant, normal operation, LOCA, SGTR, and steam line break (SLB), are considered in the evaluations.
2. For simplicity, only fifteen sensors and indicators which are related to the four representative states are considered.
3. The possibilities of sensor failures are considered. For simplicity, the NPP operator is assumed to believe that all the fifteen sensors have an equal unavailability (0.001) and that each sensor has three failure modes - fail-high, stuck-at-steady-state, and fail-low.
4. It is assumed that the NPP operator believes that the probability distribution for Z_is, i.e. $p(Z_i)$s, are given as follows:

   $p(Z_i)=\{0.999,0.0001,0.0008,0.0001\}$

5. Without any observation, the initial probability distribution for the plant state in assumed to be as follows:

   $P(x)=\{0.9997,0.0001,0.0001,0.0001\}$

6. Two performance shaping factors are considered operator expertise and operator stress level.
7. Indicators are classified into two types: analogue and digital indicators.
8. It is assumed that operators without the CPS do not use check-off provisions, and that the CPS provides a function for check-off provisions.
9. The possibilities of action error in the manual control are considered.
10. Owing to the fact that we do not have estimated values about the reliability and the effect of the fault diagnosis system and operation validation system, three reliability levels are assumed for these systems: 95 %, 99 %, and 99.9 %.

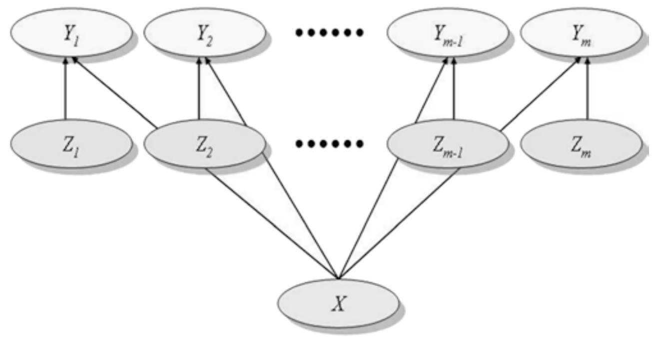

Fig. 2.6 Model of operator's rules on the dynamics of the plants [27]

11. For simplicity, operation processes of one operator are considered.
12. It is assumed that a human operator is able to detect wrong results of the fault diagnosis system, and to correct his/her wrong decisions by providing appropriate advice to the operator support systems. It is also assumed that skilled operators have more capabilities against those cases than novice operators.

2.3.1.2 BBN Model for Situation Assessment of a Human Operator

The proposed model in this work is developed based on the Kim and Seong's situation assessment model. Figure 2.6 briefly summarizes the structure of the Kim and Seong's model for situation assessment and definitions of the variables. X indicates the plant state, Z_i ($i=1,2,\ldots,m$) indicates various sensors, and Y_i ($i=1,2,\ldots,m$) indicates various indicators. The variables are defined in mathematical form as follows:

$$X=\{x_1,x_2,\ldots,x_l\} \tag{2.1}$$

where, l = Number of plant states

$$Y_i=\{y_{i1},y_{i2},\ldots,y_{in_i}\} \tag{2.2}$$

where,
$i=1,2,\ldots,m,$
m = Number of indicators,
n_i = Number of states of the indicator

$$Z_i=\{z_{i1},z_{i2},\ldots,z_{in_i}\} \tag{2.3}$$

where,
$i=1,2,\ldots,m,$
m = Number of sensors,
n_i = Number of states of the sensor

It is assumed that operators have deterministic rules on the dynamics of the plant. The deterministic rules on the dynamics of the plant can be described using conditional probabilities, as follows:

$$P\left(y_{ij}\mid x_k\right)=\begin{cases}1 & \text{if } y_{ij} \text{ is expected upon } x_k\\ 0 & \text{if } y_{ij} \text{ is not expected upon } x_k\end{cases} \tag{2.4}$$

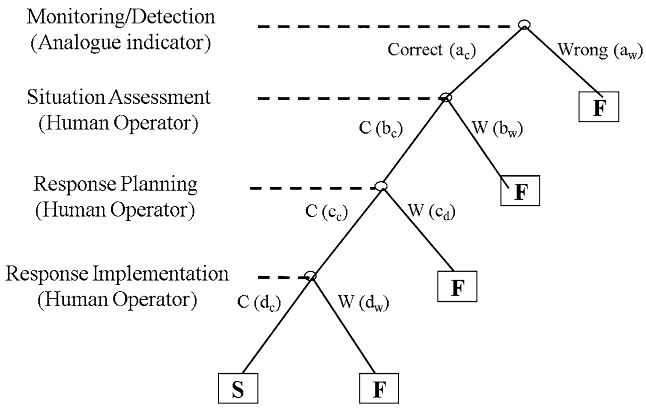

Fig. 2.7 HRA event tree with no operator support system

It is assume that NPP operators use the Bayesian inference to process incoming information, so that the situation assessment of human operators is quantitatively described using the Bayesian inference. The details of the explanation are described in Kim and Seong [25, 27]. Mathematically, if the operators observe y_{ij} on the indicator Y_i, the probability of a state of the plant x_k can be revised as follows:

$$P\left(x_k \mid y_{ij}\right) = \frac{P\left(y_{ij} \mid x_k\right) P\left(x_k\right)}{\sum_{k=1}^{1} P\left(y_{ij} \mid x_k\right) P\left(x_k\right)} \tag{2.5}$$

2.3.1.3 HRA Event Trees

The situation assessment model of Kim and Seong [25] considers only sensors and indicators. Therefore, the model is modified by adding nodes related to the operator support systems and operator's cognitive process. HRA event trees are used in order to define the relations among those nodes in the modified BBN model. Figure 2.7 shows the basic HRA event tree, which does not include any operator support system. The final operation result is correct, only if all tasks over the four steps are correct. In Fig. 2.7, a_c and a_w indicate the probabilities that a human operator reads an analogue indicator correctly or incorrectly, respectively. Likewise, b_c and b_w indicate the probabilities of correct and incorrect situation assessment by a human operator; c_c and c_w indicate the probabilities of right or wrong operation selection by a human operator without checkoff provisions; and d_c and d_w indicate the probabilities as to whether a human operator performs an action correctly or not.

If digital indicators are used instead of analogue indicators, the HEP in reading digital indicators should be used instead of that for analogue indicators. In this case, the structure of the basic HRA event tree is not changed while changing Wrong(a_w) as e_w which indicates the HEP in reading digital indicators. Also, if a function for check-off provision is provided by the CPS, the HEP for omission error should be changed to an HEP that considers check-off provision. In this case, the structure of the basic HRA event tree is not changed while changing W(d_w) as. g_w which indicates the HEP for omission error when a function for check-off provision is provided.

However, when a fault diagnosis system or an operation validation system is used, new branches should be added to the basic HRA event tree of Fig. 2.7, because those systems detect erroneous decision-making and provide an additional opportunity to correct such errors. For these new branches f_c and f_w indicate the probabilities whether or not the fault diagnosis system generates correct results, and h_c and h_w indicate the probabilities whether or not the operation validation system detects operator's wrong actions. Additionally, three parameters are considered with respect to recovery probabilities. These parameters represent the situations where the decision of the human operator is different from that of the operator support systems. The whole HRA event tree that considers these parameters is shown in Fig. 2.8. The recovery probability q means that the human operator does not change his/her correct decision even if the fault diagnosis system generates wrong results.

Owing to the fact that the fault diagnosis system provides a list of possible faults and their expected causes, operators are capable of identifying inappropriate recommendations from the fault diagnosis system based on their knowledge and experience. Thus, q represents the probability that the human operator recognizes wrong diagnosis results from the fault diagnosis system, while r indicates the recovery probability that the human operator changes his/her decision according to correct results of the fault diagnosis system when he/she assesses the current situation incorrectly. When operators assess the current situation incorrectly, they can identify their faults by consulting the correct diagnosis results of the fault diagnosis system. r represents the probability of such cases.

2.3.1.4 Evaluation Scenarios

The evaluation scenario comprises the occurrence of SGTR with the common cause failure (CCF) of pressure sensors of the pressurizer in a Westinghouse 900MWe-type pressurized water reactor NPP. The simulator that we used is the compact nuclear simulator (CNS) [28]. From the simulation, it was revealed that the diverse plant protection system (DPPS) will not generate an automatic reactor trip signal, and that the engineered safety feature actuation system (ESFAS) will not generate an automatic safety injection actuation signal due to the CCF of pressurizer pressure sensors. In this situation, operators have to correctly understand the state of the plant as well as manually actuate reactor trip and safety injection.

In the evaluation scenario, operators are required to perform two operation tasks against two evaluations. The operation task in the first evaluation is to trip the reactor manually

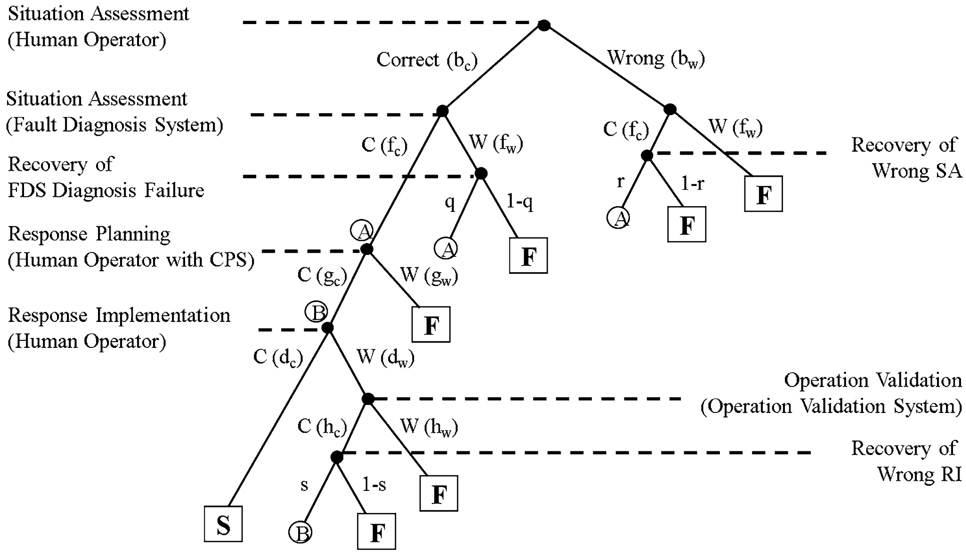

Fig. 2.8 HRA event tree with four operator support systems

and the operation task in the second evaluation is to isolate the failed SG. Under these conditions, the failed pressurizer pressure sensors cause the DPPS to fail to trip the reactor automatically. Therefore, operators have to diagnose the current status correctly and trip the reactor manually. Operators also have to identify the failed SG and isolate it.

Evaluations are performed for the following seven cases.

Case 1: No operator support system is used and the indicator type is analogue.

Case 2: The indicator type is digital.

Case 3: The indicator type is analogue and the fault diagnosis system is used.

Case 4: The indicator type is digital and the fault diagnosis system is used.

Case 5: The indicator type is analogue and a CPS is used.

Case 6: The indicator type is digital, and the fault diagnosis system and the CPS are used.

Case 7: The indicator type is digital, and the fault diagnosis system, the CPS, and the operation validation system are used.

For all cases, HRA event trees and BBN models are constructed.

2.3.1.5 Evaluation Results

The results of the evaluations are obtained using the implemented BBN models and several observations were obtained as follows:

1. Operator support systems were worthwhile in reducing the operation failure probabilities of operators.

   According to the results, when an operator support system is not used, the failure probability of a reactor trip operation is 0.017444 for a skilled operator. However, when four operator support systems supporting major cognitive activities are used and the reliabilities of the fault diagnosis system and the operation validation system are both 99.9 %, the failure probability is reduced by 71.4 %. For a novice operator, the failure probability without an operator support system is 0.023344, but with all operator support systems having 99.9 % reliabilities the failure probability is reduced by 70.1 %. For a failed SG isolation operation, the failure probability of a skilled operator without an operator support system is 0.022820, and that of a skilled operator with all operator support systems having 99.9 % reliabilities is also reduced by 70.9 %. For a novice operator, the failure probability without an operator support system is 0.028994; with all operator support systems having 99.9 % reliabilities it is reduced by 64.2 %.

2. Adverse effects were observed with low reliable operator support systems.

   Positive effects of support systems were shown when the systems have very high reliability, 99.9 %. Moreover, if the fault diagnosis system and the operation validation system have 99 % reliabilities, the operator support systems yield good results. However, if the reliabilities of the operator support systems are 95 %, degraded results are obtained. In this case, the integrated operator support system increases the failure probabilities in almost all cases. The results show that the reliability of an operator support system is very important in terms of enhancing the operator's performance.

3. Less-skilled operators were more affected by operator support systems than high skilled operators.

   The results of both the first evaluation and the second evaluation reflect good outcomes of the operator support systems. According to these results, the effect of the operator support systems is greater for less-skilled operators than for highly skilled operators. In the first evaluation for

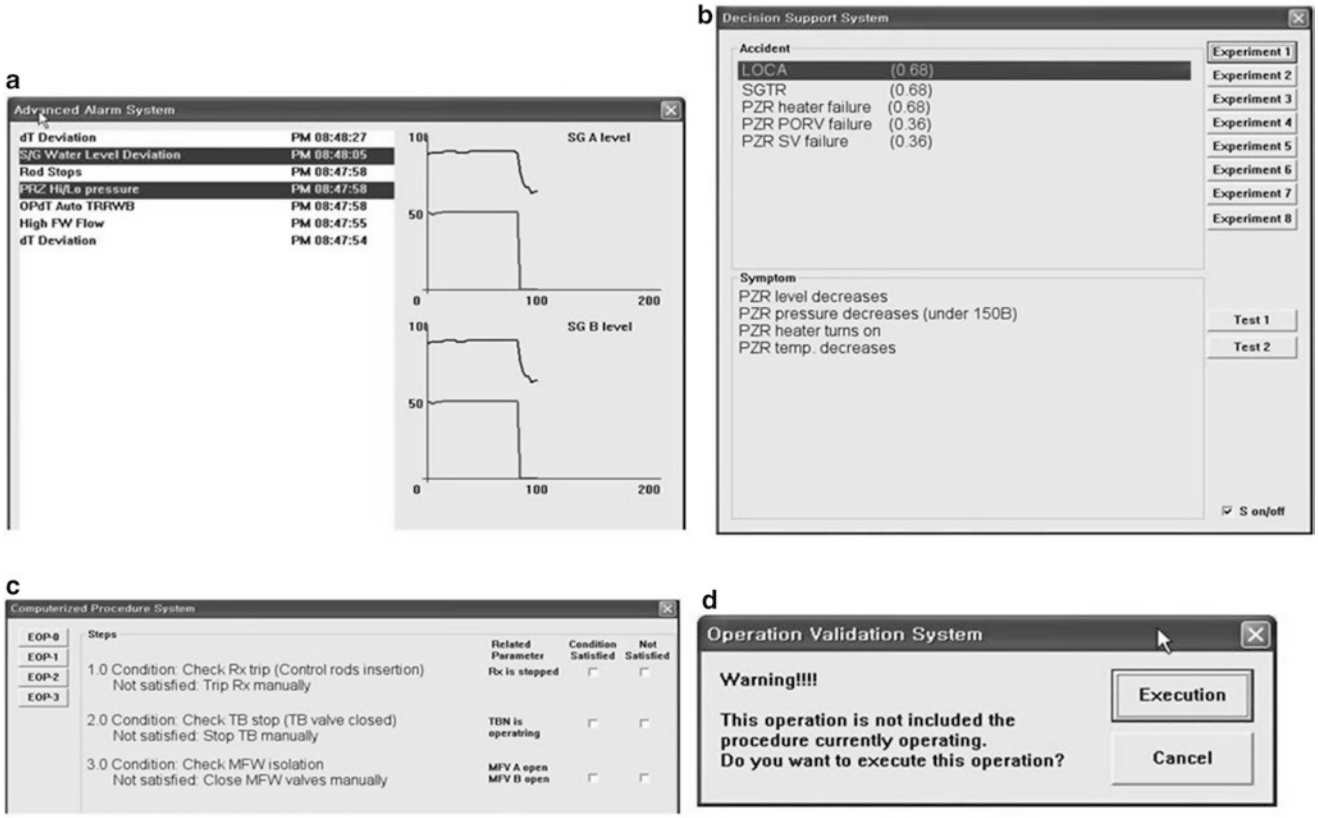

Fig. 2.9 The prototype of operator support systems. (**a**) The advanced alarm system; (**b**) The decision support system; (**c**) The computerized procedure system; and (**d**) The operation validation system

99.9 % reliability, the failure probability decrement by the operator support systems is 0.012456 for skilled operators, and that for novice operators is 0.016354. Similar results were also obtained from the second evaluation.

2.3.2 Experimental Evaluation Using Workload and Accuracy

Research on how to experimentally estimate the impact of an operator support system on operator performance has been reported previously in the literature. In most experimental studies, operator performance using operator support systems, such as information aid systems, is estimated by the quality and accuracy of a diagnostic performance [29] as well as by other various subjective or objective measurements. Subjective methods such as the NASA-task load index (NASA-TLX) and modified Cooper-Harper (MCH) have been employed to measure a subject's mental workload. For a modernized interface consisting of computer displays, the number of navigated windows and time spent for a diagnosis could be used as the criteria for evaluating operator performance [10]. The authors experimentally evaluated the operator support systems with measures of accuracy and workload [7].

2.3.2.1 Implementation of the Target System

The simple prototypes of the operator support systems were implemented for the experiments. The prototypes is implemented based on the FISA2/PC micro-simulator [30, 31], and has four operator support systems to support cognitive activities as shown in Fig. 2.9: an alarm system for monitoring/detection activity, a fault diagnosis system for situation assessment activity, a CPS for response planning activity, and an operation validation system for response implementation activity. In a prototype of the alarm system, alarm information is provided with its occurrence time. Currently activated alarms are highlighted with the color red. If a subject clicks an alarm in the list, the trend graph of the related parameter of the selected alarm is displayed in the right side of the function window (See Fig. 2.9a.). The fault diagnosis function provides a list of possible faults for a given situation, including a certainty factor and expected symptoms. In this function, if subjects click a possible fault, then they can obtain a list of expected symptoms of that fault which can be used as the information to judge the possible fault is correct or not (See Fig. 2.9b.). A prototype of CPS provides check-off provisions. If the information aid is activated, the values of the parameters related to the steps are displayed to the right of those steps (See Fig. 2.9c.).

When a subject attempts to execute an inadequate operation that is not included in the EOPs, a warning window pops up by the operation validation function. If the subject clicks the "Execution" button, the operation will be executed. If the subject clicks the "Cancel" button, the operation will not be executed (See Fig. 2.9d.).

2.3.2.2 Experiment Conditions and Measures

The subjects were 17 graduate students from the Department of Nuclear and Quantum Engineering at KAIST. They ranged in age between 24 and 39 years and each had more than 3 years of nuclear engineering experience. The experiment was conducted in seven sessions. First, participants studied NPP systems using system manuals and the simulator that would be used in the experiment. They then received a lesson on the usage of the simulator and an explanation of the decision support functions. The subjects subsequently practised with the simulator. Next, they took a written test on seven events that would appear in the main experiment. In the written test, subjects were asked to choose symptoms for given fault events from a provided list. After the wrong answers were corrected, they were asked to memorize the symptoms of those faults. The purpose of this procedure was not only to test the soundness of the subjects' understanding of NPP systems, but also to construct a library of the symptoms of the failed systems. The subjects were also instructed to solve two diagnostic problems in an exercise with the simulator. Finally, in the main experiment, the participants were asked to diagnose the seven events.

Subjects were asked to identify the seven events: (1) LOCA, (2) SGTR of SG A, (3) SGTR of SG B, (4) feed line break (FLB) of loop A, (5) FLB of loop B, (6) SLB of loop A, and (7) SLB of loop B. All of the events are accidents wherein some pipes or tubes are broken and, consequently, coolant is leaking. Subjects had to deduce the nature of these events from changes in plant parameter values, as these events do not produce any change of the systems or components in this simulator. In total, 20 experiments were performed for each subject. The experiments consisted of 5 events of a LOCA, an SGTR, 4 events of an FLB, and an SLB, and 2 random events. If the number of each event is fixed, then subjects may be able to guess the next event. In order to prevent the prediction of next experiment event, 2 events were selected randomly. Moreover, the sequence of aid types was determined irregularly. We should figure out that the change of subject performance is caused by support systems or learning effects. Therefore, irregular sequence of support types was considered to minimize the learning effects. Seven levels of support were compared in the experiments: no aid (N), alarm system only (A), fault diagnosis system only (F), alarm system and fault diagnosis system (AF), CPS only (C), alarm system, fault diagnosis system, and CPS (AFC), all the four support systems (ALL). If a subject diagnosed an event as a LOCA or an SGTR, then he/she was asked to perform corresponding operations according to the simplified EOPs. After each task was completed, the subjects were immediately asked to subjectively rate their experience using a software-version of NASA-TLX [32].

Workload and accuracy of the operations were used as the measures of operator performance. Since the most important factor is how many times an operator makes errors, the accuracy of operations was firstly selected as one of the measures. As the second measure, the workload was used to represent the potential of the errors. High potential of mistakes, caused by lots of information or high stress, may cause more frequent errors. In this study, the potential rate of mistakes was quantified by the workload. There are other performance measures such as the spent time for diagnosis. However, the changes of plant status are very rapid in the experiments events, because all the events are about coolant leaking caused by pipe ruptures. In fact, almost variable changes occurred in the first 1 minute, and most of the subjects finished their diagnosis tasks in 80 s. Therefore, the diagnosis time was not considered as a measure in this work.

Workload was measured by NASA-TLX [33]. The accuracy of an operation is represented by its failure probability. The failure probability is obtained based on two errors: diagnosis error and operation error. A diagnosis error indicates that a subject has failed to correctly identify a situation. An operation error is any of the three kinds of errors observed in the experiment. The first is an omission error wherein a subject omits a step that should be performed. The second is proceeding to an inappropriate step because of a condition mismatch. The last is the execution of an action that should not be performed. Failure probabilities were obtained by considering these two major error types.

2.3.2.3 Evaluation Results

In the experiment results, several trends were observed as follows:

1. The workload was reduced in almost all the cases.

   For diagnostic tasks, only four aid types relating to the monitoring/detection and situation assessment activities were considered: N, A, F, and AF. The results showed the trend that an adaptation of support systems resulted in a workload reduction. During LOCA, the workload of 13 of the 17 subjects decreased while 4 subjects had an increased or an only slightly changed workload (within 5 %). 15 subjects showed decreased workload and 2 subjects showed increased or almost equal workload in SGTR events. During the FLB events, the workload of 11 subjects decreased and for the rest it did not. During SLB events 13 subjects showed decreased workload and 4 subjects showed an increased or only slightly changed workload.

2. Workload was greatly reduced in more complex situations.
   We calculated the amount of information which should be managed by a subject in each accident in order to establish the relation between task complexity and the change of workload. The information flow model proposed by Kim and Seong [34] was employed and it was apparent that the reductions of workload in complex situations are more than those of less complex situations. For example, SGTR had more information flow (30.69 bits) than LOCA (18.34 bits) and the average reduction of the workload was greater in SGTR case.
3. Human error of misdiagnosis was reduced.
   Each subject was asked to diagnose a total of 28 events; 7 events per each aid level (N, A, F, and AF). During LOCA events, subjects committed an average of 1.12 diagnostic errors while using N aids during 7 events, but the average error rate was reduced to 0.71 using an AF aid. Diagnostic error rates of 1.24, 0.47, and 1.94 errors were observed for subjects acting without an aid during SGTR, FLB, and SLB events, respectively, but these rates were reduced to 0.94, 0.53, and 0.82 errors while using an AF aid. In LOCA, SG TR, and SLB, misdiagnoses were reduced by about 37 %, 24 %, and 57 %, but FLB cases showed a slightly increased number of errors. The support systems showed reduction of the number of misdiagnoses in most cases.
4. Human error of misaction was reduced.
   Without the CPS, subjects omitted a step by an average of 0.29 times, and misjudged conditions by 0.29 times during the 16 total steps of LOCA events. When the CPS was provided, omission errors decreased to 0.06 times and commission errors also reduced to 0.24 times. Using the CPS, omission errors were reduced from 0.35 times to 0.12 times, and the commission errors were reduced from 0.18 times to 0.06 times during 18 actions in SGTR events. A wrong action execution occurred 0.24 times during 9 control actions performed without the operation validation system, but that rate was reduced to 0.06 times when using the operation validation system during LOCA. During SGTR, average misaction rates were reduced from 0.35 to 0.12 through the provision of the operation validation system.

2.4 Issues and Perspectives for Operator Support Systems

In this paper, three papers for the development of an integrated operator support system and its evaluation were reviewed. To maximize the efficiency of the operator support systems, INDESCO was proposed based on the cognitive process of a human operator. In theoretical and experimental evaluations, positive results were also observed regarding the effectiveness of operator support systems. However, issues remain to be solved regarding the creation of practical operator support systems. Four points of views should be considered in the development and evaluation of operator support systems.

2.4.1 Trust of Operators on Operator Support Systems

The most fundamental and important factor is for an operator support system to guarantee its reliability. If an operator has doubt about the information or advice from an operator support system, the effect of the system could be negative. If an operator always has to consider cases in which the information of the support systems may be incorrect, then the information will be rendered ineffective. The theoretical evaluation results showed that accuracy of an operator support system is critical. An adverse effect of a support system was observed when the reliability of the system was reduced to 95 %.

In advanced MCRs, the support systems are not used as additional systems. Some of the raw data of a plant are processed by support systems and operators use only the preprocessed data for plant operations. In this environment, it may be more difficult to recognize incorrect information from a support system. Hence, as the roles of operator support systems increase, the reliability of the system becomes all the more critical.

2.4.2 Necessary and Useful Information

As NPPs evolve, additional operator support systems will be developed and adapted. Therefore, it is equally important to select appropriate and efficient operator support systems, and useful information in order to optimize the amount of information and maximize its efficiency. Unnecessary information or inappropriately provided information may have a negative effect such as information overload.

This situation can be observed more frequently in independent operator support systems. The generation of useful information and the optimization of information so as to retain what is necessary for the current situation are required. The CPSs were simply converted forms of paper-based procedures in the early stages. However, recently developed or developing CPSs have useful functions for providing necessary information or guidelines for operations, thus preventing obvious human errors. These functions provide useful information, but the information can be duplicated with other functions. INDESCO is a method for analyzing tasks and suggesting essential information based on human cognitive activities.

How the information of an operator support system is provided is important. Although the information of a support system may be useful, it can become useless with inappropriate designs. For example, too many interruptions of an operation validation system can have negative effects. Such a system is designed to prevent human errors such as pressing the wrong button, by double-checking the actions. However, too many interruptions cause operators to become accustomed to repeated interruptions, resulting in their becoming desensitized to them. Another good example is an experiment conducted that showed that a fault diagnosis system can have an adverse effect on operator performance [10]. In an experiment, one type of fault diagnosis system provided only possible faults without their expected symptoms or causes. Under those conditions, operators had to infer the expected symptoms and compare them to plant parameters in order to confirm the results, leading to decreased performance. On the other hand, a fault diagnosis system providing expected symptoms showed good performance.

2.4.3 Evaluation of Operator Support Systems

Operator support systems must be evaluated to prove their efficiency. However, there is no evaluation method for operator support systems which is widely accepted. It is not easy to propose an evaluation method, as the operator support systems are still in the development phase, and human operators should be considered during any evaluation. For reliable evaluations, accurate data of operator support systems are necessary, such as the design details and the reliability (or the accuracy of the outputs) of the systems. Due to the lack of operational data from operator support systems, several assumptions were made in the theoretical evaluations, and prototypes, instead of practical systems, were used in the experimental evaluations. As operator support systems are developed commercially and more operational data accumulates, more accurate and reliable evaluation results can be obtained.

There are two approaches to evaluate a system: a theoretical method and an experimental one. Each evaluation method has its own strengths and weaknesses, and adopts different measures. Therefore, in the absence of a widely accepted evaluation method, the results of comparisons of theoretical and experimental methods may be viable means of offsetting the weaknesses of each method. In fact, two evaluations reviewed in this paper showed similar results in some aspects; human errors were reduced by adapting operator support systems in most cases in both evaluations. Moreover, common intriguing trends were observed in each experiment.

The evaluation should parallel the development of an operator support system. In the design phase of a support system, many factors are considered so as to create a useful and effective system. These factors are tested to determine the faults in the system and to resolve them. However, evaluations by other teams or organizations are crucial to ensure the reliability of the system. Moreover, the reflection of the evaluation results on the system design is important, especially for highly safety-critical systems. After the development of a system, changes in the design require high costs and tremendous efforts. For more efficient and reliable system development, the evaluation should be considered during the development phase.

2.4.4 Operators' Dependence on Operator Support Systems

As aforementioned, a paramount issue when seeking to adapt a support system to an actual plant is the final decision-maker problem. This issue is akin to the automation level problem. If roles of support systems (or automation systems) increase, roles of human operators decrease. However, decreased tasks do not necessarily mean the decreased possibility of human error. A high level of automation may degrade operators' abilities. Even when some parts of operations are performed by support systems, operators should comprehend the current situation correctly and in real time. Human operators have to remain as the final decision maker due to safety and responsibility problems in NPPs. In light of this, determining the apposite balancing point between the role of human operators and that of support or automation systems is indeed important.

Highly-skilled operators know a plant very well, and comprehend the plant status precisely and quickly. Some operators with considerable experience tend to dislike changes of the plant interface because they are very familiar with the system and feel that they do not require the help of a support system. If the information of the support system is supplementary and they can operate the plant with the information, skilled operators may not want or consider the advice of the systems. However, less experienced operators are likely to use the advice of a support system and depend on the system much more than skilled operators. This trend was observed in the evaluation results. Low dependence of an operator on a support system caused ineffectiveness of the support system, while high dependence may degrade an operator's ability.

2.5 Summary and Conclusion

Operational tasks in MCRs are mind-boggling activities, and human error has been identified as the most serious cause of accidents in NPPs. For advanced MCRs, improving HMIs and developing an operator support system can help prevent human errors. Using operator support systems, the amount of information which should be handled by operators can be reduced by filtering out or integrating raw process data, which cause a reduction of the operator workload. Moreover, operators can make their decisions easier and quicker with functions such as interpreting the plant state, prioritizing goals, and providing advice. The development and adaption of an operator support system for MCR operators is a pivotal issue for advanced NPPs. In the process of installing more operator support systems into commercial plants, efficient designs and evaluation methods will continue to be critical issues. One fundamental issue in the design of an operator support system is that a human operator is the "final decision maker", while the operator support system is simply a "support" system. Support systems must not confuse a final decision maker by providing inapposite information, and must not degrade the ability of the final decision maker. To provide appropriate information, systematic and highly reliable designs and accurate evaluations are necessary. Operator support systems must guarantee their high reliability for the trust of the operator, and to provide the information that is necessary and efficient for operators. To prevent the ability of human operators from being degraded, creating an efficient balance between the roles of human operators and those of support systems is equally important. In consideration of these issues, operator support systems can be developed more systemically.

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