HUMAN-MACHINE INTERACTION IN NUCLEAR POWER PLANTS

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Advanced nuclear power plants are generally large complex systems automated by computers. Whenever a rare plant emergency occurs the plant operators must cope with the emergency under severe mental stress without committing any fatal errors. Furthermore, The operators must train to improve and maintain their ability to cope with every conceivable situation, though it is almost impossible to be fully prepared for an infinite variety of situations.

In view of the limited capability of operators in emergency situations, there has been a new approach to preventing the human error caused by improper human-machine interaction. The new approach has been triggered by the introduction of advanced information systems that help operators recognize and counteract plant emergencies.

In this paper, the adverse effect of automation in human-machine systems is explained. The discussion then focuses on how to configure a joint human-machine system for ideal human-machine interaction. Finally, there is a new proposal on how to organize technologies that recognize the different states of such a joint human-machine system.

KEYWORDS : human-machine interface, human factors, joint human-machine system, emergency operation, operator support, automated system, situation recognition

1. INTRODUCTION

Recently, the use of computers has rapidly expanded in every field of human endeavor. From the viewpoint of research on human-machine systems, we see that computers do many tasks automatically at the human-machine interface. Because computers themselves are machines, modern machine systems have a double structure of machines within machines; that is, the original machines built-in computers. The complexity of human-machine systems derives from the double-structured machine system. In these systems, computers replace the traditional human works of manual control by automatically controlling systems step by step. In addition, the problem of the human factor is emerging due to frequent human errors (or cognitive errors) in human-machine interaction. The safety problem of cognitive errors at the human-machine interface is universal, as evidenced by two severe accidents at nuclear power plants, namely the Three Mile Island accident in 1979 and the Chernobyl accident in 1986. Since then, numerous studies have been conducted on the human factor in many nuclear power plants developing countries around the world with a view to understanding the nature and characteristics of human-machine interaction and to overcome problems with the human-machine interface.

Nuclear power plants are generally large complex plants with highly automated systems. Whenever a rare plant emergency occurs, the plant operators must cope with the emergency under severe mental stress without committing any fatal errors. In addition, the operators must train to improve and maintain their ability to cope with every conceivable situation, though it is almost impossible to be fully prepared for an infinite variety of situations

In view of the limited capability of operators in emergency situations, there has been a new approach to preventing the human error caused by improper human-machine interaction. Based on the concept of human-centered human-machine systems, the new approach has been triggered by the introduction of advanced information systems that help operators recognize and counteract plant emergencies.

We now discuss the adverse effect of automation in human-machine systems, followed by human-machine systems for ideal human-machine interaction. Lastly, new proposals will be presented on how to organize technologies that effectively enable various states to be recognized for the human-machine system.

2. ADVERSE EFFECT OF AUTOMATION IN HUMAN-MACHINE SYSTEMS

The introduction of computers in human-machine systems has progressed along with the integration of information from various sensors for monitoring tasks. At the same time, automatic controllers of many types of machines and equipment are now performing tasks that were once controlled manually. As the result of automation, the role of plant operators has changed from that of a traditional manual controller to a supervisor of automated machine systems [1]. Although the automation of an individual machine or piece of equipment can save human work, an operator can manage a greater number of machines when automation is introduced. As a result, modern machine systems, such as energy plants, electric power systems, telecommunication systems, banking systems, airplanes and air traffic control systems, highway traffic systems, and rapid train systems, will grow larger and more complex with more automation. They are also vital for the infrastructure of modern society, especially with the advancement of the information era and globalization. Moreover, the safety, reliability and security of such a society depend on a dwindling number of technical experts who are struggling to keep up with the advancement of technological development [2].

The positive progress of automation is due largely to the motivation to develop economical and reliable systems with minimal human involvement. The reasons for this motivation are, firstly, to avoid human error by excluding humans from the system, and, secondly, to lessen the human workload. However, the complexity of the large computerized, automated systems has highlighted essential human problems in the human-machine interaction of safety-critical systems. The human factor, for instance, is critical in problems such as large accidents at nuclear power plants, massive electricity blackouts, and airplane accidents [2]. In this context, L. Bainbridge labeled the unreliability of humans as supervisors of innovative technical equipment in safety-critical systems as one of the “ironies of automation” [3].

According to L. Bainbridge, the expected role of operators as supervisors of automated machine systems is twofold: as a backup whenever the automated system fails, and as a manual controller of non-automated parts of the system. In practice, however, automatic machines seldom have problems and operators mostly watch the machine working smoothly. Because operators have nothing to do or rarely operate the machine by themselves, they gradually loose the knowledge and skill of operating the machine and tend to rely blindly on the machine. That is, the machine becomes a “black box” for the operators. However, if the machine suddenly fails, what happens then? The operators may be upset and try to recover the machine without knowing what to do. Such action could make the condition of the plant worse, and the operators might eventually commit a fatal error.

To avoid such dangerous relation between humans and machines, operators must be well trained for any emergency situation. However, there are numerous types of emergency situations, and it is difficult to predict the timing and nature of a crisis. The important issue here is that operators should be well trained to cope with any problem, not only from the technical aspect but also from the spiritual aspect. Therefore, even though the daily tasks of operators mostly involve the monotonous monitoring of a smooth running plant, they must maintain a high level of skill to be able to diagnose anomalies of any kind, and they need to develop a sound mind to ensure they can manage the plant safely under the pressures of time and social responsibility [2].

Bainbridge’s aphorism “ironies of automation” raised deep concerns about the patchwork development of automation, with its easily made technical advances and failure to consider human factors. Nowadays, new approaches of human-centered automation rather than traditional technology-centered automation have been extending towards the formation of a human-machine system, and the keywords of the new approaches are “keep humans in control”, “user-participation design”, and “computer support for easy understanding” [2].

3. HUMAN-MACHINE SYSTEM FOR IDEAL HUMAN-MACHINE INTERACTION

3.1 What Is the Ideal Human-Machine Interaction?

The notion of an automated plant may seem comfortable to operators but, as said in the preceding section, it can force them to undertake the difficult tasks of recovering an automated system when it fails and of making decisions in a limited time. How then can we achieve conformity in technical automation? According to T. Sheridan, there are presently two types of human-machine interaction: management by consent and management by exception [4].

In management by consent, the final decision is left to humans; that is, the automatic system does not activate unless a human gives an instruction. On the other hand, in management by exception, the automatic system waits a certain period for a human response but starts automatically if no human response is received. In both cases, the machine lets the human decide what to do, which may be uncomfortable for the human, especially. If we assume that the automated system requires human interaction, the system should therefore be equipped with a communication function that enables the human to perceive in detail every state of the machine. For instance, it should tell the human what is happening in the plant and what the human is supposed to do. Moreover, such information should be communicated in a human-centered —that is, it should be easy for the human to understand.

3.2 Model of Human Behavior at the Interface

At this point, we need to consider of the process of human thinking (human cognitive process) at the human-machine interface. Figure 1 shows the operator model of J. Rasmussen [5]. According to J. Rasmussen, the operator's cognitive behavior and action mode differ in accordance with the operator's perception of the information presented at the interface. As a result, Rasmussen claimed that the operator has three modes of action: skill-based, rule-based and knowledge-based.

In the skill-based mode, the operator unconsciously acts as smoothly as an automated multivariable control system. However, in the rule-based mode, the operator is conscious and promptly makes associative actions by remembering the relationship between the perceived state of an world situation and the corresponding action in the world situation. The relationship between the world situation, the state and the action is a mental model that the operator internally appropriates as a scheme. The skill-based and rule-based modes are automatic, thereby requiring a minimal mental load. Well-trained operators can perform actions in both modes.

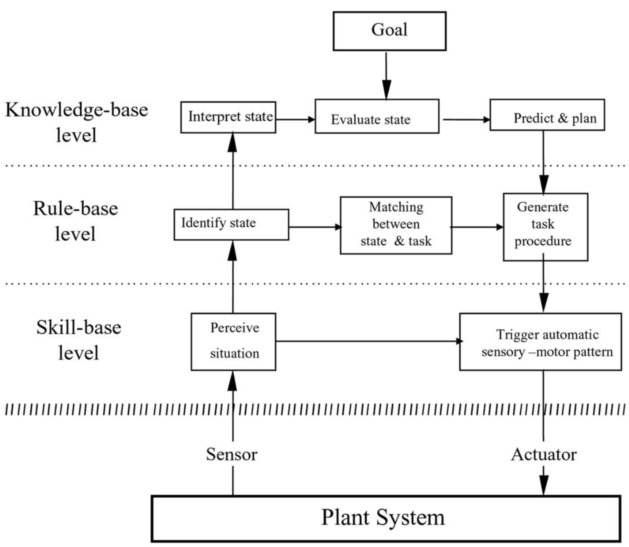

Fig. 1. J. Rasmussen's Operator model

In contrast, the mental models used in the knowledge -based mode differ from the associative relationship. In the knowledge-based mode, operators should abstractly recognize the state of the plant by using their knowledge of the semiotic relationship of the plant's configuration. That is, of its goal and function, means and ends, parts and whole. They should also recognize the logical relationship of factors such as the cause-consequence relations between the input and output variables, as well as the qualitative relations between variables based on physical equations. By using these difficult, abstract models, operators can interpret the sensor information, find the root cause of the failure, predict future trends, and then decide what to do. This type of action is intense, laborious, and time consuming, especially for a poorly trained novice. However, even well trained operators can use this knowledge-based mode when they encounter unfamiliar situations.

3.3 Human Psychology in Emergency Situations

When people encounter accidents, they often say "my head is white out". To be calm and to take a breath before acting is a good lesson for operators to prevent them from acting reflectively under a white-out condition, and the lesson may effectively prevent erroneous actions in an emergency situation.

For dealing with accidents under time restraints and high levels of stress, the following human modes were assumed when designing the operator support: (i) the operator skips cumbersome cognitive work such as interpretation; and (ii) the operator makes reflective actions whenever a stimulus is given.

3.4 Imbalance of Information in the Human-Machine System

Another difficulty of designing the interface is the imbalance in the way information is processed between the human and the computer, as indicated in the classical list of Fitts [6]. Humans process information much slower than computers, even if a rigid procedure has been predetermined. Computers, on the other hand, can promptly process many kinds of information and display the results in many different styles. However, a human operator who is upset in an emergency situation finds it almost impossible to recognize and understand all the information presented at the interface, even if the computer lessens the cognitive load that it presents to the operator. Another human handicap is the speed of interaction with the machine. To send a query to the computer, the operator must use cumbersome tools such as a keyboard or mouse. The information transfer from the human to the computer is another factor in the imbalance of information in the human-machine system.

As a result, it is imperative that the machine displays only indispensable information, and that it transmits the information in a form that can be easily understood by the human.

3.5 Direct Support and Indirect Support

We now discuss an effective method of presenting information at the human-computer interface. Based on the principles of human nature in emergency response situations, the method comprises direct support and indirect support. Direct support means that the presented information need not be interpreted by humans, or that humans need only follow the machine's instructions, or that that humans behave only as a manipulator in accordance with presented information. On the other hand, indirect support means that humans are asked to do something such as interpret the information presented by the computer.

However, for real operator support during an emergency at a nuclear power plant, it is difficult to anticipate all the probable situations and to supply the support information to the automated system. As a result, it is impossible to construct a system solely of direct support. Moreover, for the direct support method, there is no assurance that humans will follow the machine's instructions. As a result, our operator support system comprises direct and indirect support functions. For both the direct and indirect support system, the information should be presented to the human in such a way that the human cognitive load is at a minimum level and the human can clearly perceive what is happening in the plant.

4. SUPPORT TECHNOLOGY OF STATE RECOGNITION FOR HUMAN-MACHINE SYSTEM

There are three effective methods of indirect support that produce an interpretation load that is acceptably light for operators in emergency situations. The three methods are as follows: (i) use of short sentences to explain the plant's status and the operator's instructions; (ii) graphic representation with user-friendly icons and symbols; and (iii) positive use of patterns with certain types of graphics to show the dynamic response of the system, thereby enabling human interpretation and diagnosis to be replaced by simple pattern matching. Figure 2 shows an example of the third method, in which case a medical doctor diagnoses a patient's heart disease and then compares the patient's ECG chart with a typical ECG wave of a certain heart dysfunction. With direct support by positive use of graphic representation, the diagnosed results of what happened in the process can be transmitted with a light cognitive load to the operator [7].

In the following sections, we discuss various new methods of effective support technology that help operators

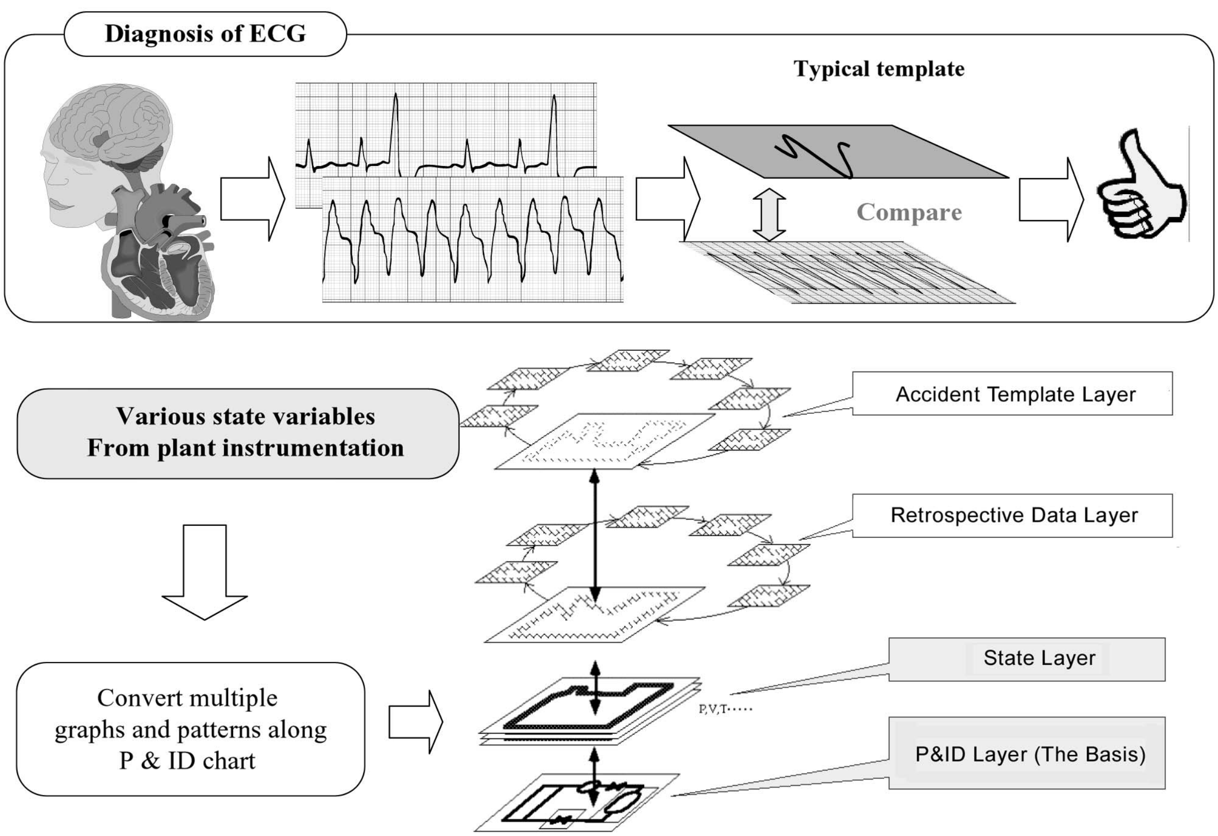

Fig. 2. Diagnosis by Pattern Matching Like the Way of Diagnosing a Heart Dysfunction by Comparison of ECG Patterns

to recognize the status of emergency situations in a nuclear power plant.

4.1 Meta Information of a Plant and Hierarchical Representation

In cases of high stress and time limits, the operator must be given an accurate message with a minimum of information. The information could be from a single process sensor but generally contains crucial “meta information”, which is highly abstracted, symbolic information from many different process signals. The safety parameter display system (SPDS) in most nuclear power plants displays this kind of meta information (regarding the safety functions). Graphical representation of the meta information should enable operators to easily understand the current situation with the highest level of abstraction or the least number of representative variables.

On the other hand, how can meta information represent the structural configuration of a real plant system? It achieves this representation by using different degrees of abstraction for the plant functions to present macro information and micro information. The presentation of macro information means displaying all the information in a simple way so that the user can grasp the entire system at a glance. The presentation of micro information refers to a control board that shows graphs of parameters related to a certain subsystem, thereby enabling operators to see variations in the processes of the plant’s subsystems.

Fig. 3. Overview of an Advanced BWR Control Room

The main control boards of many advanced nuclear power plants use hierarchical presentation of macro and micro information. Figure 3 shows the main control room of a Japanese Advanced BWR plant. At this plant, macro information is mainly displayed on a large screen, whereas the micro information is displayed on CRT screens on the operators’ control desk.

The ideal configuration of a human-machine system has hierarchical ordering of meta information. That is, macro and micro information of the entire plant are

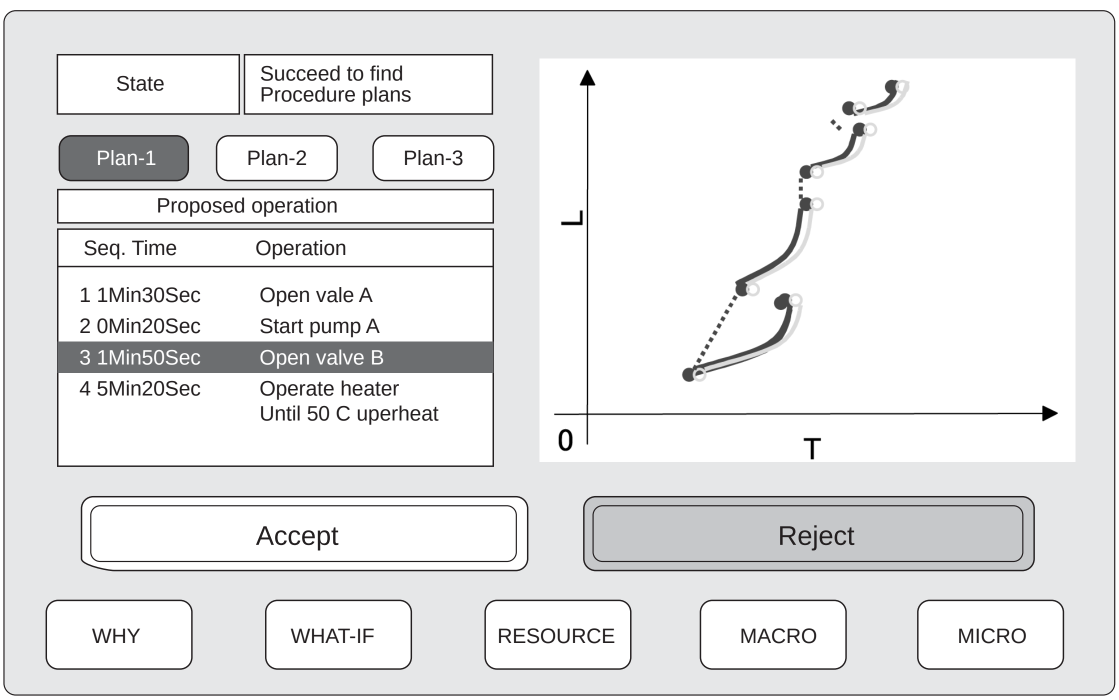

Fig. 4. Meta Information Display

presented with a high level of abstraction and a small quantity of information. In addition, the meta information is presented along the stated order of plant information and implemented with flexible navigation over different levels of abstraction.

4.2 Meta Information Interface for a Human-Machine System

Figure 4 shows a meta information display for a human-machine system[8]. This type of display represents a form of management by consent, whereby the automatic system first automatically searches for plausible operation procedures and then shows the results as alternative plans as indicated by Plan 1, Plan 2, and Plan 3 on the left side of the figure. In this situation, the optimal plan, Plan 1, is indicated by reverse presentation in which the corresponding operation procedure is shown as a sequence of operation numbers, along with the timing and content of the operation. Whenever the operator agrees with the proposed plan, the operator should push the accept button.

Whenever the operator monitors the plant behavior that will be brought about by the execution of Plan 1, the operator should watch the graph, which is shown on the right-hand side of Figure 4. This graph is an example of effective meta information presentation that enables the operator to easily grasp the status of the plant. The horizontal axis of the graph T shows how much time is available until the state of the reactor becomes dangerous. The perpendicular axis L, on the other hand, shows how much time is left until the safety critical parameter enters a dangerous zone. Therefore, the point of origin of the T-L plane is the dangerous point. Since the safety status of the plant is always represented by a moving trajectory in the T-L plane, the operator can easily judge the likely outcome of operations that let the point move towards the point of origin.

Nuclear power plants are generally recovered by starting and stopping the pumps and turning the valves on and off. Consequently, the jumps seen in the trajectory curve of Figure 4 correspond to such manual recovery operations. In Figure 4, the black trajectory curve indicates the curve predicted by the automated system, while the grey curve indicates the trajectory of the real process. Both curves have the same trajectory. However, if there is a large deviation between the two curves, the operator can stop the automatic function by pushing the reject button to switch to manual operation.

The meta information displayed in Figure 4 shows how the automatic system executes the plan. In addition, the real trajectory of the automatic operation is superimposed on the predicted trajectory in T-L plane, enabling the operator to grasp the progression of the plant process and to determine whether the automatic operation is following the prediction. In addition, the five buttons shown in the lower part of Figure 4 are the navigation buttons to other displays. The resource, macro, and micro buttons lead to displays that the operator can use when operating the system manually. The resource button lists all the available resources for recovering the plant. The macro and micro buttons correspond to representations of the macro and micro information. The what-if and why buttons are explained in the next section.

4.3 Human-Machine Dialogues with “Why” and “What-if” Displays

In the “why” display, the automatic system explains why it proposes an operational plan. This display can be realized with the aid of a logic chart. As shown in Figure 5, the automatic system uses binary logic or discrete data. In Figure 5, diagram 1 uses the binary logic of a combination of AND/OR (which is normally called a fault tree) to describe the relationship between the reason for the failure of a plant’s safety function and several root causes of failure (such as Cause 1, Cause 2, and Cause 3). When the operator pushes the start button, Cause 1, Cause 3, and Cause 5 eventually appear sequentially in the order of graphs 2, 3, and 4. As a result, the operator can easily confirm the failure of a certain safety function and, by tracing the fault tree, can determine why it failed.

When an automatic system proposes a certain plan of action, inquisitive operators like to ask the automatic system to evaluate the effect of modifying the proposed plan before deciding whether to use the plan as originally proposed or to modify it. The “what-if” display, which is shown in Figure 6, responds to such requests, and this dialogue typifies the dialogue between humans and machines with existing technology.

In this case, the operators would like to have a more favorable plan than that proposed by the automatic system. In particular, they would like to know *how* slowly (Modifier: M) they should *open* (Verb: V) *which valve* (Object: O) in *which subsystem* (Subsystem: S).

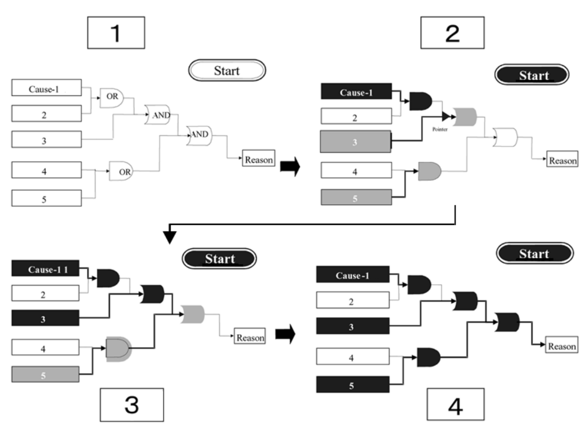

Fig.5. The “Why” Display

Figure 6 shows a display through which the operator can ask the automatic system questions in relation to S, O, M, and V. In the "what-if" display, which is shown in the left-hand side of Figure 6, when the operator selects in turn the options among the icons for items S, O, M, and V, the selected results are displayed in short sentences in the four boxes below the four items. After confirming the selection, the operator pushes the OK button to send the request to the automatic system. The predicted trajectory of the process change is then displayed on the same T-L plane, as was explained in Figure 4. (See the T-L plane in the right-hand side of Figure 6.) This trajectory is the answer from the automatic system. As a result, the dialogue between the operator and the automatic system can be smoothly conducted on the "what-if" display with the aid of symbolic representation.

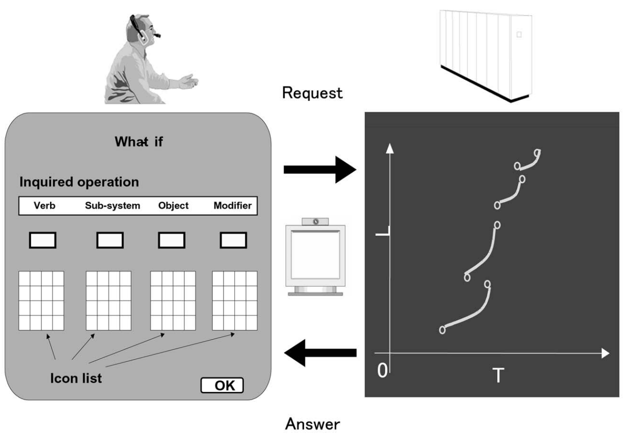

Fig.6. The "What-If" Display

4.4 Etiquette of the Human-Machine System

As automation progresses in human-machine systems, the etiquette of machines becomes critical. According to C.A. Miller, machines should observe the following etiquette [9]:

(i) They should display information that is useful for the current moment, but should do no more than that.
(ii) They should base their advice on adequate proof and know what is true.
(iii) They should help develop effective human-machine interaction.
(iv) They should present unambiguous information.

However, the problem lies not in the etiquette of machines but of humans. Even if the machine etiquette is incorporated into the design of the machine, the human factor is more cumbersome because of the personality differences of humans. It is difficult to attain symbiosis of humans and machines if humans blindly believe the machine's information or neglect the information entirely. As a result, we need to prepare guidelines that describe how humans should respond to automated machine systems. The minimum etiquette of humans should be as follows:

(i) They should not neglect machines. (This means they should respect machines as intelligent members of staff; that is, as an ensemble of engineering wisdom.)
(ii) They should not depend entirely on machines. (They should not unreasonably adapt to machines because there are always faults in human-made machines. Rather, they should continually strive effort to improve machines.)
(iii) They should understand the three P's of machine designing, principle, perspicuity, and philosophy.

In this context, perspicuity refers to the quality a human's interaction with machines. For example, humans may soon neglect a message from a machine if the machine continues to send monotonous messages or meaningless alarms each time the human interacts with the machine. The word perspicuity suggests that humans should grasp the quality of information transmitted by the machine.

Most people think automated systems should convey information by correctly representing it at important moments, and prudent people seek as much information as possible to prevent human error. The interface for a human-machine system should ideally be designed to present appropriate information so that any individual user, regardless of personality, can understand the information. The system should also be able to carefully analyze the human's behavior to obtain the correct prediction.

5. CONCLUSION

The research and development of the human-machine interface for nuclear power plants progressed remarkably in the two decades after the Three Mile Island and Chernobyl accidents. This progress was mainly due to the rapid progress of computer and information technologies. Although the generic nature of humans is not as changeable as the progress of computers, the understanding and knowledge of human-machine interaction have deepened due to the efforts of applied cognitive psychologists who are interested in human-machine systems. In addition, although humans can create machines that have high quality, high reliability, and a high level of functions, it is difficult to improve humans in the same way. Humans are fundamentally the same throughout history, and even the same person varies only slightly over time. Therefore, harmony between humans and machines is fundamentally difficult to attain unless machines positively attempt to understand humans.

In this paper, I reviewed the research on emerging human interface technologies for human-machine systems. In addition, I have proposed several ideas on how automated systems should act towards humans who manage complex machine systems (such as helping operators to recognize the status of a machine). In spite of the apparent oddity of a machine knowing itself and informing a human of its own problems, this notion is the future reality of human-machine interaction. It is imperative therefore that machines are honest with humans and that humans be cleverer than machines. The issues of etiquette for human-machine systems should therefore be a top priority in the development of future I&C R&D in nuclear power plants.

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