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An Information Theory-based Approach to Modeling the Information Processing of NPP Operators

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Abstract

This paper proposes a quantitative approach to modeling the information processing of NPP operators. The aim of this work is to derive the amount of the information processed during a certain control task. The focus will be on i) developing a model for information processing of NPP operators and ii) quantifying the model. To resolve the problems of the previous approaches based on the information theory, i.e. the problems of single channel approaches, we primarily develop the information processing model having multiple stages, which contains information flows. Then the uncertainty of the information is quantified using the Conant' s model, a kind of information theory.

Key Words : information processing, information theory, quantification, workload

I. Introduction

A nuclear power plant (NPP) consists of three components: the machine system, the man-machine interface (MMI), and human operators. With technological advances, the machine system of a NPP, especially the instrumentation and control (I&C) system, has been digitalized and automated. New plants are designed to be highly computerized, while conventional ones are scheduled to be upgraded by computerization [1]. With respect to the MMI, attempts to improve its usability and understandability have been made *since the Three Miles Island accident*, which revealed that the operators could not handle various and voluminous information from the conventional MMI. The MMI is becoming more intelligent, integrating larger display panels, soft controls, and operator support systems. In accordance with changes in the I&C systems and MMIs, the role of an operators change from a manual controller to a supervisor or a decision maker.

To meet this development' s challenges requires knowledge not only of the physical capabilities of man, but also of man' s cognitive capacities and tendencies. The technological advances have changed the nature of the man-machine interface from an emphasis on operator physical tasks to cognitive tasks. The costs and consequences of ignoring the cognitive functions of the MMIs are noted in technological failures, for example, the Three Miles Island accident [2]. However, the operator's cognitive process in relation to a NPP has not yet been sufficiently studied. Further efforts are necessary to study information processing of human operators for the safety of NPP.

The ultimate objective of modeling the cognitive behavior of operators of nuclear power plant (NPP) is to improve the system design. In order to achieve this duty, it is important to develop a very detailed operator model in which particular emphasis will be given to the modeling of operator error [2]. The operator model, especially contextual approach, suggests several aspects which are important in designing to support human beings in complex tasks [3]. Another objective is to improve the training of operator. Different training methods are suited to different types of cognitive process. Systems which involve control automation or cognitive automation (decision support systems) need to be designed so that operators can develop and maintain the perceptual-motor and cognitive skills they may need during manual take-over.

Information theory, along with Bayes's rule, is the best-known quantitative approach describing human information processing. In much of human performance theory, investigators are concerned not only with how much information is presented to an operator but also with how much is transmitted from stimulus to response. Using these concepts, the human being is sometimes represented as an information channel [4]. Merkel and Donders found, via Stimulus-Response (S-R) experiments, that reaction times increased logarithmically with the number of alternatives [5]. Shannon quantified the concept of uncertainty mathematically in terms of how information can be encoded in a message [6], while refining the concepts of information and uncertainty. Hick [7] and Hyman [8] extended the work of these early authors and Shannon by applying their concepts and results to psychological studies of human communication and perception. Hick and Hyman found that choice reaction time increases as a logarithmic function of the amount of information and not just the log of the number of alternatives. These studies regarded a human operator as a single information processing channel that merely responds to a set of stimuli. Their experiments were also performed on simple tasks such as voice response or key pressing response to light. Thus, this simple stimuli-response model is inadequate to effectively describe complicated behaviors of NPP operators such as knowledge-based work, information integration, and information reduction, which are required by the technical advances in NPP.

This paper proposes a quantitative approach to modeling the information processing for NPP operators. The focus of the present paper will be on i) developing a model for information processing of NPP operators and ii) quantifying the model. To resolve the problems of the previous approaches based on the information theory, i.e. the problems of single channel approaches, we primarily develop the information processing model having multiple stages, which contains information flows. Then the uncertainty of the information is quantified using Conant's model, a kind of information theory. This paper attempts to combine the qualitative information processing model with a quantitative approach.

2. Development of the Information Processing Model for NPP Operators in MCR

After reviewing qualitative models for human cognitive behavior and observing/interviewing the trainees in the Retraining Center for Kori 3&4 units, we developed an information processing model for NPP operators. In this work, the information processing model for NPP operators is developed as a channel consisting of multiple processing stages.

Prior to describing how the model is developed, it is necessary to look into the characteristics of operators' behavior and their environments. Woods and Roth have summarized the characteristics of human operator's behavior as follows [9]:

1) There is a need for continuous monitoring or tracking how the disturbance develops, rather than a single diagnosis.
2) The team must revise their responses to changing circumstances, based on a changing assessment of the situation, including the mental model of plant dynamics.
3) How one sees the situation at any point depends in part on how the incident has been perceived up to that point.
4) There is a need to anticipate what could happen next, and as a consequence to revise monitoring strategies.
5) The situation requires incremental decision making with repeated inspection of the process and adjustment to problem solution.
6) Adequate feedback is essential.

These characteristics show that a contextual model is more adequate for describing operators' dynamic behaviors than a sequential model. A sequential model has some difficulties in describing the continuous observation and the revision of the responses and the strategies. The chief characteristics of sequential models are: there is a one-directional sequence of processing, from stimulus reception to response execution; output of a stage is usually a simple mapping of its input; there is a set sequences of processing stages, though some the stages may be omitted; and other knowledge is referred to, if at all, only at later stages in the processing. On the other hand, the contextual model shows the flexible way people do the thinking which underlies an overt sequence. The terms " sequential" and "contextual" emphasize the comparison between a set sequences of processing stages and the choice of processing topic as a function of context. Details of the differences between the two models can be found in [3].

Consider an operation wherein an operator detects an anomaly from an alarm and closes a valve. In this operation the operator received the information from the alarm and generated the action, "close a valve." Namely, it is thought that the information of the alarm was transformed into another type of information, action. From the viewpoint of the information channel, therefore, we can consider that NPP operators acquire the information from various kinds of environments and formulate output information that may be in the form of actions or decisions. According to the knowledge they contain, the eight categories of the transformed information are defined. The definitions are shown in Table 1. The alert does not carry any specific information about severity, but just a warning about existence of changes. The goals of NPP operators can be summarized as follows.

1) safe power generation in a normal state
2) stabilization of NPP, that is, the compensation for the immediate influence on some vital performance parameter under the observed abnormal state
3) fault diagnosis

Figure 1 shows an overview of the information processing model for NPP operators. In the proposed model, an operator is represented as an information processing channel consisting of multiple stages, as mentioned previously. The information processing stages are depicted by the rectangular boxes in the figure. The circles depict the input and the output information of the stages; actually, the inputs and the outputs should be included in the stages, since the information processing is carried out in the stages (For the convenience of drawing, this figure was constructed in this manner). The arrows represent the flows of the stages and the information. As shown in the figure, the feedback arrows that represent the movement of stages to the previous one do not carry any information. This means that when operators move to the previous stage, the information already processed in the current stage is temporally stored in the working memory or is forgotten. This model shows not only the sequence of information processing, but also the information flow processed in the operator. By modeling the information flow, the model can show the information integration and the information reduction in the stages. The model also presents various information flows from the operators' environments. In addition, the model is a contextual one that can reflect the characteristics of the operators' dynamic behaviors.

In the processing stage of the proposed model, a set of inputs is matched with operator's knowledge or mental model and then transformed to another type of output information, usually higher abstract information, as shown in Figure 2. If the input information is not matched or is validated as irrelevant information, it may be blocked. The detail of each stage and the information flow in the stages are as follows.

2.1. Information Acquisition

In this stage, operators relate raw data to the different physical and logical variables of the plant. This stage assigns a certain cognitive meaning to the signal information coming from the environments. All types of information can be generated as output information. The output information varies according to the sources of the input information and the stage at which it will be transferred. Operators may generate a sign from the control panel or verbal messages from other operators. Operators may also transform the signal information from the fault diagnosis system to the symptom or the cause. Figure 3 (a) shows the information flow in the stage of the information acquisition. The information in the box of stages represents the output information generated in the stage.

2.2. Event Acknowledgement

In this stage operators detect and acknowledge normal or abnormal changes of the situation in the plant. This stage is the starting point of cognitive activity in working memory. This stage receives the input of the sign information from the stage of information acquisition. The sign information may come from alarms in the control panel or from verbal messages from other operators. An alert is produced as output information. In this stage, operators may immediately take some actions in response to the alert. They may push the button of "acknowledgment" on the alarm annunciator panel and/or notify the occurrence of the event to the other operators. Figure 3 (b) shows the information flow in the stage of the event acknowledgement.

2.3. Identification

In the identification stage, operators identify the state of the plant. This stage usually interprets the signs from the previous stage and generates the symptom as an output. They may also receive symptoms via verbal messages from

Table 1. The Definitions of the Transformed Information

Information	Definition
Signal	• The information that exits in the environments or is provided by the environments • A set of indicators and alarms or verbal messages from the other operators. • Sensory data presented on the control panel or the CRT. Ex) indicator #1:15.2, indicator #2: 12.3
Sign	• A certain feature in the environment and the connected condition [10] • Specific meanings about signal and significant or meaningful information Ex) the data is related to steam generator #1, its value is 15.2, the data is related to steam generator #2, its value is 12.3
Alert	• A warning information notifying the occurrence of some changes in NPP
Symptom	• A perceived state of the plant • The information which is related with a change of the state of the plant and the phenomena produced by the anomaly. Ex) Temp of steam generator #2 is low and decreasing.
Cause	• The information about the location of the anomalies and the root of the cause Ex) The cause of the anomaly is the fault of the feedwater pump.
Goal	• An ultimate objective of actions which are carried out in response of the anomalies
Procedure	• The steps to follow for problem solving • Written or memorized procedure to be performed in order to achieve the goal. Ex) general operating procedure (GOP), abnormal operating procedure (AOP), emergency operating procedure (EOP)
Scheduled Action	A series of actions chosen and scheduled according to the procedure

other operators, validate them and generate symptoms. If an alarm processing system has been installed in the MCR, it may provide signs or symptoms for operators. The symptoms from the alarm processing system or the other operators may be blocked if the operator validates the symptoms as improper information. If operators judge that the stabilization of the plant is more urgent than the diagnosis of the anomalies, they can skip the diagnosis and go to the planning stage. As an immediate response, operators may ask local operators by phone to identify the status of a system or equipment and notify their symptoms to the other operators. Figure 3 (c) shows the information flow in the identification.

2.4. Diagnosis

In this stage, operators try to find the location and the cause of anomalies or faults. This stage generates hypotheses from the symptom they receive concerning the meaning of the status information they have received, i.e., the hypotheses concerning the cause and the location of the anomalies. In addition, it tests the hypotheses. This stage usually obtains the symptoms from the prior stage and generates the causes including the location of the anomalies. The other operators or a fault diagnostic system may provide symptoms for the operators. The diagnosis stage may also obtain the causes from the other operators or the fault diagnostic system

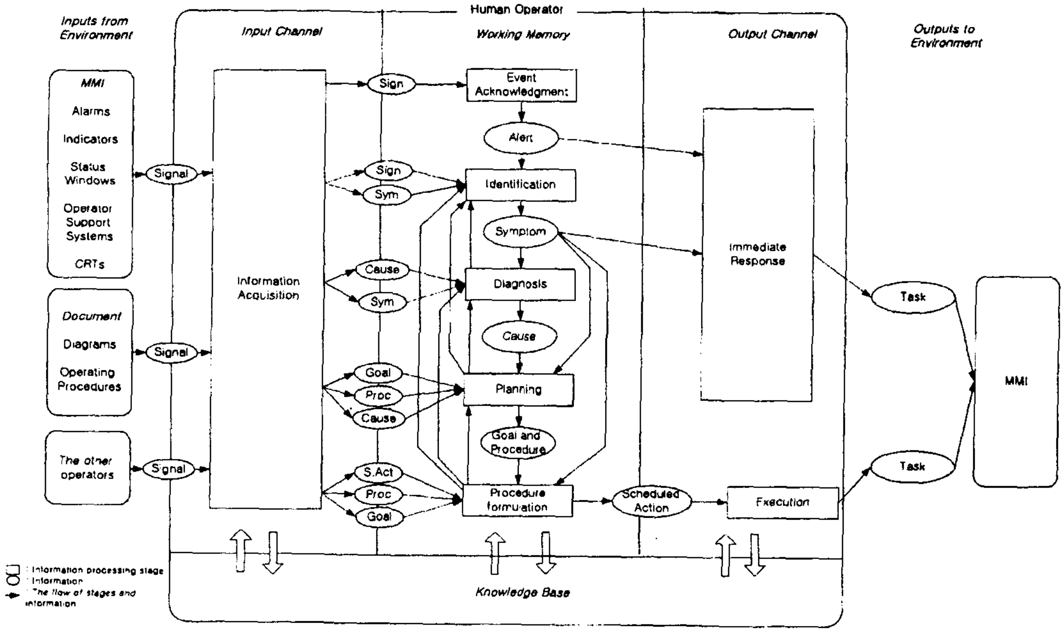


Fig. 1. The Overview of the Suggested Model for the Information Process in NPP Operators

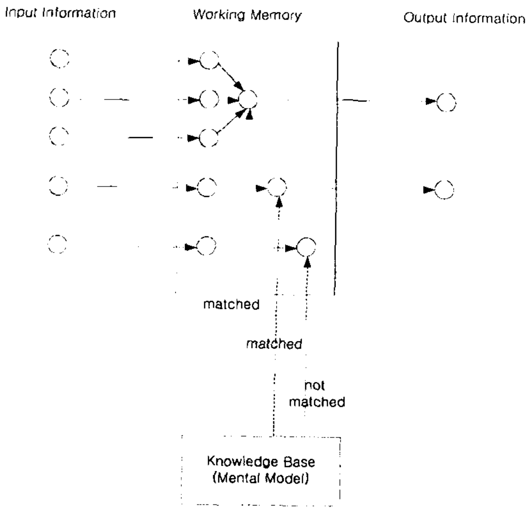


Fig. 2. Information Matching Model in Each Stage

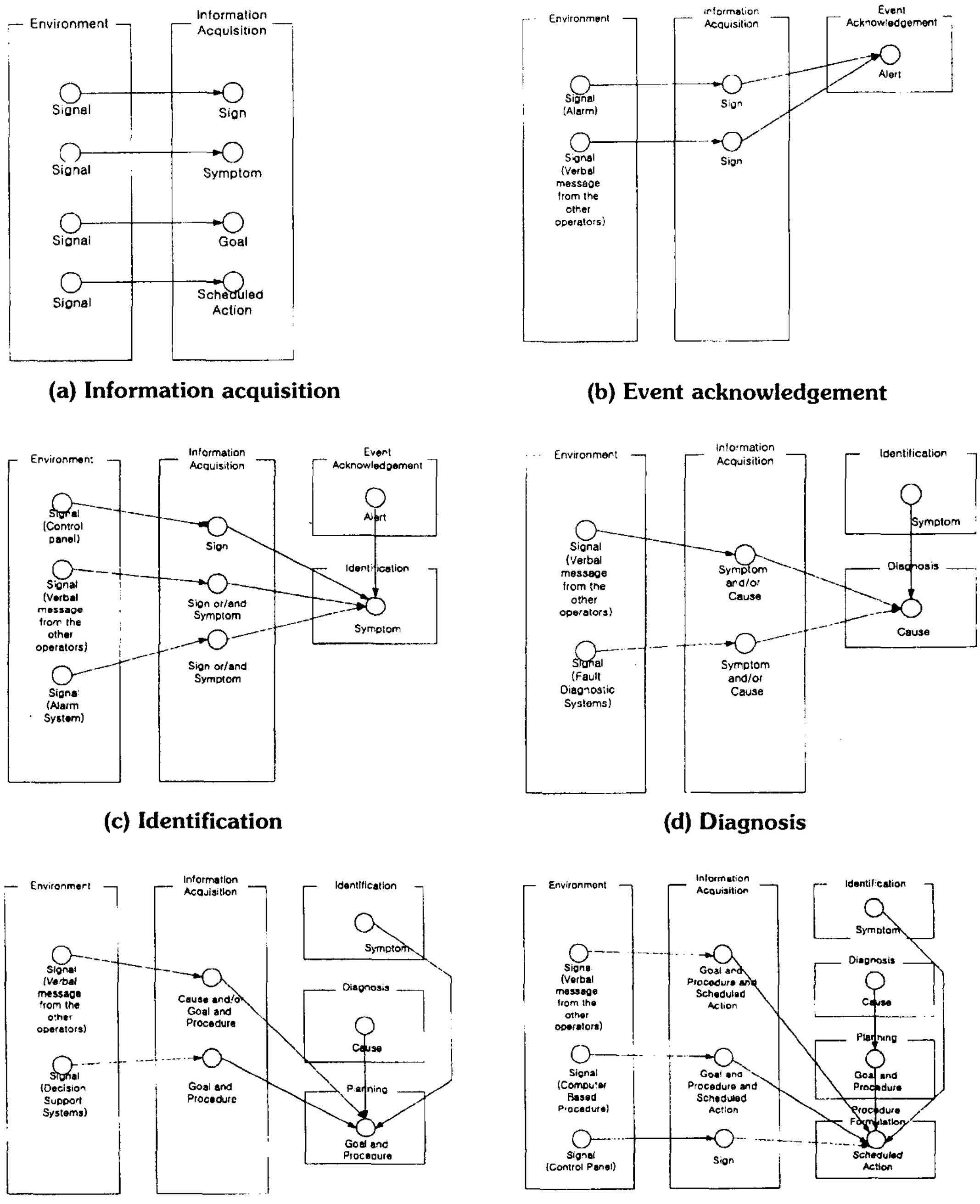
and then validate them. Figure 3 (d) shows the information flow in diagnosis.

2.5. Planning

In the planning stage, operators predict the situations that the plant may reach and decide the goal that should be achieved. Then the procedure to be followed is determined according to the goal. The main input in this stage is the cause obtained from the previous stage or the other operators. At this stage, the operators may also receive symptoms from the identification stage. They may also get the goal and the procedure from the other operators or a decision support system. The output information is the goal and the procedure. Figure 3 (e) shows the information flow in planning.

2.5. Procedure Formulation

In this stage, the procedure to respond to the situation is formulated in order to achieve the goal. The procedure absolutely depends on the goal and



(a) Information acquisition
(b) Event acknowledgement
(c) Identification
(d) Diagnosis
(e) Planning
(f) Procedure formulation

Fig. 3. Information Flow in Each Stage

involves the tasks necessary to reach the goal. The procedure may be written, memorized through experience and training, or given as oral instructions by the other operators. The main inputs of this stage are the procedure and the goal from the prior stage or the other operators. This stage may also receive symptoms or signs since they are necessary as conditions for carrying out the procedure. The output information is the scheduled action to be executed and chosen. Computer based procedures or computerized operating procedures may help the operators' activity in this stage. Figure 3 (f) shows the information flow in procedure formulation.

3. Quantification of the Information Processing Model

Entropy has been widely used as a quantitative measure of uncertainty in many areas including thermodynamics, information theory, biology, decision theory, and sociology. Shannon, who largely originated information theory, proposed the most important information quantity, entropy, which played a central role in information theory as a measure of information, choice and uncertainty [6]. Entropy can measure system complexity based upon the postulate that system complexity depends on the uncertainty associated with identifying the exact current status of the system [11]. Shannon's entropy, which measures the uncertainty and information formulated in terms of probability theory, is a system characteristic playing an important role not only in communication, but also in decision making, classification, recognition, and so on [12]. Kang and Seong have attempted to evaluate the complexity of the interface and alarm system, based on information theory [13], [14], [15]. They have found that information theory is a useful tool for evaluating the MMI quantitatively.

3.1. Conant's Model

Conant used information theory to better understand real-world systems, although he admits that "there are obvious dangers in applying information theory, designed for use under the severe mathematical constraints of stationarity and ergodicity, to a real-world system not thus constrained" [16], [17].

Information is related to uncertainty. By the information theory, the amount of information, bits, is simply equal to the base 2 logarithm of the inverse of probability, i.e.,

$$H_i = \log_2 \frac{1}{p_i} \tag{1}$$

where Hi is the amount of information and pi is the probability of the occurrence of event i. The average information conveyed by a series of events with different probability is computed as

$$H = \sum_{i=1}^{n} p_i \log_2 \frac{1}{p_i} \tag{2}$$

where

p_i : probability of occurrence of event i, and

n : total number of possible events.

Equation (2) is exactly the same as the mathematical definition of entropy in statistical mechanics. An important characteristic of Equation (2) is that when the events are not equally likely, H will always be less than its value when the same events are equally probable.

The amount by which two variables are related, i.e., they are not statistically independent, is measured by the transmission between them, denoted as $T(X_1{:}X_2)$ and defined through probabilities, or by

$$\begin{aligned} T(X_1 : X_2) &= H(X_1) + H(X_2) - H(X_1, X_2) \\ &= H(X_1) - H_{X_2}(X_1) \\ &= H(X_2) - H_{X_1}(X_2) \end{aligned} \tag{3}$$

$H_A(B)$ denotes the amount of information in A, conditional on B; it is the amount of information in A when B is known. $H(X_A,X_B)$ denotes the total information corresponding to the combined occurrence of A and B. The transmission is a measure of relatedness between variables, which accounts for its usefulness in system science. $T(X_A:X_B)$ fall in the interval $[0, \min\{H(X_A), H(X_B)\}]$, being 0 if and only if A and B are statistically independent and maximum if and only if one variable determines the other.

Conant considered a system S as an ordered set of variables $S = \{X_1, X_2, \cdots, H_n\}$. Those variables in S that can be directly observed from its environment constitute output variables. The set of these output variables is denoted as $S_o = \{X_1, X_2, \cdots, H_k\}$, with $1 \leq k \leq n$. The remaining variables within S are internal variables, denoted as Sint. Hence, $S = \{S_{int}, S_o\}$. E denotes all relevant variables outside S. Next, Conant obtained an expression for the total information rate F (in bits/s) as a measure of the total processing activity within S

$$F = F_t + F_b + F_c + F_n \quad (4)$$

The different constitutes of F can be defined as follows (the upper bar indicates rates):

$F_t = T(E : S_O)$	Relatedness (transmission) between the environment and the output
$F_b = T_{S_O}(E : S_{int})$	Transmission between the environment and the internal variables when the output is known
$F_c = T(X_1 : X_2 : \cdots : X_n)$	Transmission between the variables of S
$F_n = H_E(S)$	Information in S when E is known

(5)

The dimension of these terms is bits. Readers can see the detail of the calculation and the meaning of each term in [16], [17].

3.2. Quantification of the Information Processing Model

This work considers an operator as an information processing system and then each stage corresponds to a subsystem.

The term F_t is the thruput rate and is a measure of the relatedness between input and output. The thruput rate represents the amount of the output information that is matched with input information in each stage and then transferred to the next stage. Given a finite input and no blockage, information integration of the operators lowers the thruput rate. This means that as more input information converges on the smaller number of outputs in the stage, the thruput rate decreases.

The second term is the blockage rate and represents the effort needed by S in order to block irrelevant information. The blockage rate represents the amount of information that is not transferred to the next process. This means that the irrelevant information is received from the previous stage and the information is blocked in this stage. The blockage rate is related to the fact that an MMI provides the operator with unnecessary information in the cognitive process. The blockage also occurs when the operators' information process moves back to the previous stage because of a deficiency of input information, or operators revise the information.

The coordination rate F_c represents a measure of the total coordination between all the variables in S. The coordination rate represents the amount of information processing needed to obtain a coordinated action among the system variables of S.

The noise rate Fn represents the amount of internally-generated information in the process. As mentioned above, the noise rate is the rate of "free will," since it corresponds to behavior which has no apparent cause. Considering operators don't create any information independent of inputs during the operation, we can assume that the noise rate is zero. Control operation in the MCR should be performed in responding to the situation, based on the procedure or the operator's knowledge from training and experience.

Therefore, we can redefine the information flow in each stage as follows.

$$F = F_t + F_b + F_c \tag{6}$$

The total information flow for a system is expressed as

$$F = \sum_{i=1}^{N} F^i . \tag{7}$$

i : a subsystem of a system S

The total information flow is represented by the sum of the total rate for subsystems.

An example of an operator's information processing is illustrated in Figure 4. This example is for a fault of "Pressurizer Pressure Control Ch #X Fail High", derived from the operating procedure of Yongkwang unit 1&2. All the information that is connected to the information of "PZR PR CONT CH #X FAIL HIGH" in the diagnosis stage is the essential information for situation awareness. The operator acquires the information about RCS temperature and Pressurizer level from the other operators and generates the unnecessary information of "RCS temperature decreasing." A fault diagnostic system helps the operator reach the correct diagnosis result. Without the support the operator might conclude the wrong result of "PZR SPRAY V/V FAIL OPEN", which has similar symptoms to the desired result. When the current processing stage move to the previous one, the information in the stage is not transferred. The information is temporally stored in the working memory or forgotten, as mentioned above. Therefore, since there are not the feedbacks of the information but the feedbacks of stages, no feedback arrow between information exists in the example. An example in the figure is shown in the case of the information that is not transferred to the next stage and blocked in the stage, namely, "RCS TEMP is decreasing," and "PZR SPR V/V FAIL OPEN". This means that the information is validated as improper one and in this situation operators may move to the previous stages and attempt to get more information.

Table 2 shows the results quantifying the example shown in Figure 4. For convenience of calculation we assumed that the inputs from environments have even probabilities about "on" and "off" and so each has 1 bit, even though in a real situation the probabilities of the case "on" are much higher than "off". In the case of many-to-one mapping, it is assumed that the output will be generated only if all the inputs are "on". In the stage of information acquisition, there exists no blockage since all the inputs are transferred to the identification stage. In the proposed approach, the blockage results from two kinds of information processing. One is the information blocking, such as "RCS TEMP is decreasing," that the information does not transferred to the next stage. The other is the reduction of amount of the information caused by many-to-one mapping.

The information flow F is the amount of the information processed in the operator. It is also a measure of the uncertainty of a situation conveyed to the operator. The amount can be represented by the sum of thruput, blockage, and coordination. Information processing is the task which maps (or integrates) a set of inputs into a set of outputs, reducing the uncertainty.

The amount of the processed information

Table 2. The Information Flow of the Example

Stages \ Terms (bits)	Thruput	Blockage	Coordination	Total information flow
Information Acquisition	8	0	8	16
Identification	2.27	4.73	3.15	10.15
Diagnosis	0.12	3.15	0.53	3.8
Total				29.95

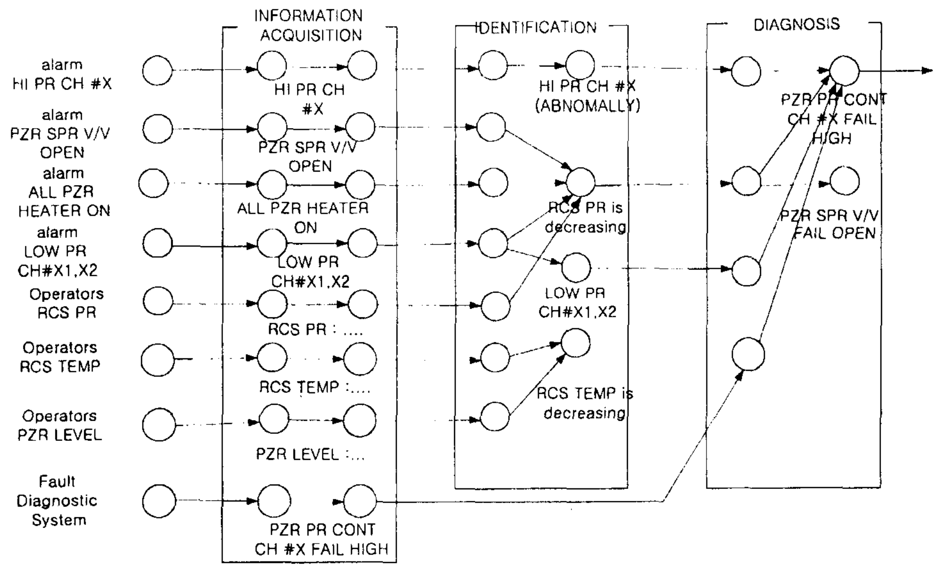


Fig. 4. An Example of an Operator's Information Processing for the Fault of "Pressurizer Pressure Control Ch #X Fail High"

corresponds to the operator' s workload in the information processing task. Each term (thruput, blockage, and coordination) in this approach can be interpreted as a workload:

1) the thruput, which is the workload generated by the operator' s work of transferring the outputs to the next stage;
2) the blockage, which is the workload generated by the work of blocking and reducing the inputs in the stage;
3) the coordination, which is the workload generated by the work of finding the relatedness between the inputs in the stage.

If a task demands a load beyond the operator' s capacity of information processing, workload related errors may arise. Therefore, in order to relieve the operators' workload, it is necessary to manage the information and to reduce the amount of the information provided to operators as much as possible within the capacity of the operators in terms of information processing. Since the thruput represents the outputs related to inputs, the amount of information transferred to the next stage should be reduced to minimize the thruput.

With respect to blockage, it is necessary to reduce the information blocked in information processing, i.e., to provide operators with minimal irrelevant information. The coordination represents the relatedness between variables (i.e., information) in the stage. Therefore, by providing inputs independent of one another we can reduce the coordination. These three terms are not respectively separated, but rather they are related to one another. The reduction of blockage may cause an increase of thruput. Thus, we can reach the conclusion that the best way to reduce the operators' workload is to present them with minimal information.

5. Conclusions

We have quantified the amount of information in information processing, using information theory. To model the complicated information processing of NPP operators, a human operator was defined as an information processing channel having multiple stages. By defining the transformation of the information in stages, we can quantify the proposed model. The total information flow F quantified is the amount of the information processed in the operator. Each term (thruput, blockage, and coordination) can be also considered as the workload that is made to do the respective works. As a future work, we also have a need to experimentally find out the relation of the information flow to the response time and performance of operators.

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