ISBN: 978-3-95450-254-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS1991-S17AIA04

Development of Operator Thinking Model and Its Application to Nuclear Reactor Plant Operation System

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ABSTRACT

At first, this paper presents the developing method of an operator thinking model and the outline of the developed model. In next, it describes the nuclear reactor plant operation system which has been developed based on this model. Finally, it has been confirmed that the method described in this paper is very effective in order to construct expert systems which replace the reactor operator's role with AI (artificial intelligence) systems.

I. INTRODUCTION

A nuclear reactor plant has the following special features. How to control and operate it are the important subjects of research and development.

(1) Because it contains a lot of radioactive substances, it would harm public in case of the accidents. Therefor, its high safety is required.
(2) Because it gives society a great deal of economic loss in case of the stop of its operation, its high reliability is required.
(3) Because it is composed of many components which have different characteristics, its dynamic behavior is very complex.

In order to control and operate a nuclear reactor plant with such features adequately, the reactor operator's role is important and his burden is heavy specially in the case of the plant anomalous states. According to past serious accidents of a nuclear plant, it proved that mis-judgement or mis-operation is one of influential factors which would harm the safety and reliability of a nuclear reactor plant. Considering information processing characteristics of man and machine, the task allocation between both is decided as follows.

(1) Man is allotted to irregular tasks which require general judgement and decision making.
(2) Machine is done to regular tasks which require high speed processing.

In a current nuclear reactor plant, man takes the initiative of control and operation, and machine supports him. Therefor, various operator support systems are under development and some of them are applied to in-service real reactor plants.[1]

In order to improve further the reliability of a nuclear reactor plant, it is necessary to reduce occurrence probability of human error by replacing the reactor operator's role with the AI system. Such a plant called an autonomous one is under research and development. [2][3] In order to realize this plant, it is necessary to define a framework of the knowledge base and inference mechanisms of the AI system. One effective method would be to develop the operator thinking model and to utilize it. Based on this motivation, operator's thinking process and decision making process in the case of the plant anomalous states were studied using the full scope operator training simulator for "JOYO", the first experimental fast breeder reactor in Japan. In next, the operator thinking model was developed based on the experimental results. [4]

Still more, a nuclear reactor plant emergency operation system has been developed based on the above model. This system is an expert system which substitutes the operator's action to prevent a trip and maintain the safety of a plant in case of emergency.

II. DEVELOPMENT OF OPERATOR THINKING MODEL

At fist, the developing method of an operator thinking model is presented. In next, findings obtained by experiment and the developed thinking model are described in brief.

A. Method for Developing Operator Thinking Model

A.1 Experiment Condition

(1) Object plant : Experimental fast breeder reactor "JOYO"
(2) Simulator to be used : The "JOYO" full scope operator training simulator
(3) Experiment case

In order to attain our experiment purpose, malfunctions which satisfy the following conditions were selected.

1) They are able to be simulated by the "JOYO" training simulator.
2) They are so complex as an expert operator must think and judge.
3) They are not so complex as an expert operator cannot diagnose at all, for example, too multiple contingent malfunctions.

A.2 Simulator Experiment

The outline of typical experiment case is shown as follows.

(1) Object persons : One operator and one supervisor
(2) Selected malfunction
- Sodium leakage from the main primary B loop
- Failure that sodium leakage sensors do not operate
- Failure that sensors which detect the difference of rotation speed between A and B primary circulation pumps do not operate

A.3 Outline of Tasks for Development

Tasks for developing an operator thinking model are composed of the excusion of experiment and carried out after it.

Experimental arrangement around the training simulator is shown in Figure 1.

(1) Collection of data

ISBN: 978-3-95450-254-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS1991-S17AIA04

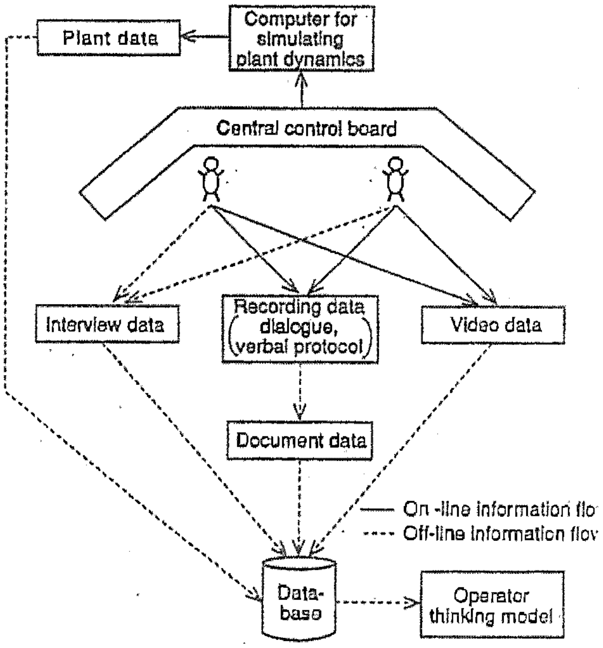

Figure 1. Experimental arrangement and data acquisition.

The following data were collected.
1) Record about an operator's verbal protocol and dialogue
2) Video camera recordings about an operator's behavior and changes in indicators on central control board of simulator
3) Analog trend data of plant dynamics
(2) Interview after experiment

Verbal protocol and dialogue data are complemented by interviewing an operator directly.

(3) Transforming record into document data

Record such as verbal protocol, interview data, etc. is transformed into document data (raw data).

(4) Making analysis data

An operator's thinking process is analyzed on the basis of raw data, and then analysis data were made.

(5) Making operator thinking model

The model which expresses universally an operator's thinking process is made by generalizing synthetically the above analysis data.

A.4 Format of Document Data

The following three document sheets are used during the development of an operator thinking model.

(1) Interview sheet
- Time when the object events of interview have occurred
- Content of interview

(2) Verbal protocol sheet
- Time when the object voice has been produced
- Content of voice

(3) Thinking process analysis sheet

Both raw data which contains the above (1),(2) and analysis data which is made on the basis of raw data are described according to the sheet shown in Table 1.

Table 1 Format of thinking process analysis sheet

Classification	Raw data					Analysis data				
Name	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)

(1) Time when events have occurred
(2) Analog trend data of plant dynamics
(3) Display information
(4) Operator's behavior
(5) Verbal protocol
(6) Segment of verbal protocol
(7) Analysis results of thinking process
(8) Recognition information of plant state
(9) Knowledge stored in long-term memory
(10) Information stored in short-menory

A.5 Analysis Method of Thinking Process Data

(1) The collected data are transformed into document data and are arranged according to the format described in Table 1.
(2) The verbal protocol data are decided into segments (the minimum units which have meaning).
(3) The macro-structure of thinking process is identified through classifying segments into basic thinking elements.
(4) The following knowledge and information used in basic thinking elements are clarified.
1) Knowledge stored in long-term memory
This knowledge is possessed by an operator before simulator experiment
2) Information stored in short-term memory
This information is memorized by an operator after the start of simulator experiment.
3) Recognition information of plant
The information flow in operator is shown in Figure 2. Think-

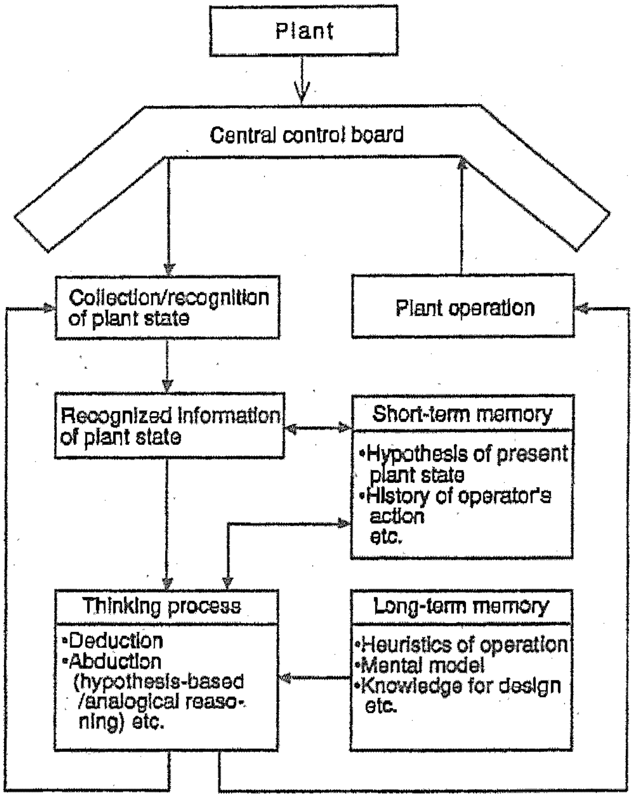

Figure 2. Information flow in operator.

ing and judging by the use of the above knowledge and information, an operator operates his plant and collects plant information.
(5) Analysis results of thinking process are arranged according to the sheet shown in Table 1.

B. Findings Obtained by Experiment

The findings were made clear in regard to the operator's procedures for decision making and action.
(1) When an operator encounters a complicated anomalous state, he acts based on his knowledge.
(2) An operator diagnoses the current plant conditions and makes his decision mainly based on hypothesis-based reasoning.
(3) When an operator cannot make suitable hypothesis only based on his shallow knowledge concerning the current plant conditions, he tries to use deep knowledge. The hypothesis is composed of the primary cause/degree/propagation of anomaly.
(4) An operator understands the relationship between goals and means to attain them in the plant on the basis of the mental model that is hierarchically composed of the operation goals and means.
(5) An operator monitors the plant conditions periodically. In the case when he faced the states of emergency, he carries out operation action against them preferentially.

C. Developed Operator Thinking Model

Based on the above findings, the thinking model was developed as shown in Figure 3. In the model, thinking and decision making procedure is as follows.

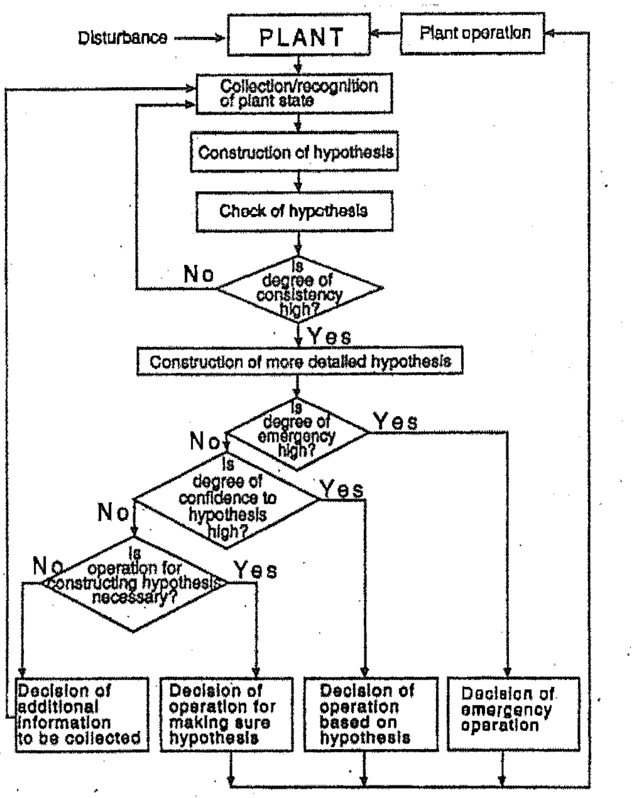

Figure 3. Developed operator thinking model.

At first, an operator actively collects and recognizes the plant information. Thereafter, he constructs a hypothesis concerning the current plant state then checks the consistency between the newly identified plant state and the hypothesis. If he recognizes that the consistency is high, he makes more detailed hypothesis. Otherwise, he makes new hypothesis. In the later portion of the procedure, he makes decision to take action depending on degrees of emergency and his confidence concerning the hypothesis. Possible actions he may take are collection of additional information, operation to make sure the hypothesis, operation based on the hypothesis, emergency operation, and so on.

It is desirable to decide plant operations based on the suitable hypothesis. But an operator decides emergency operations according to the model shown in Figure 4 in case the degree of emergency of a plant increases so rapidly that he cannot construct the suitable hypothesis. The outline of this model is as follows.

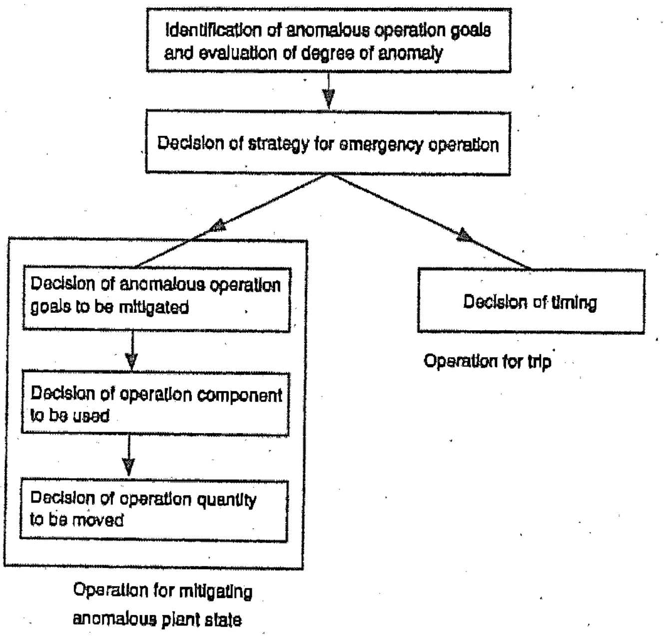

Figure 4. Decision model of emergency operation.

Based on plant display information and the mental model which is hierarchically composed of operation goals and means, an operator identifies anomalous operation goals, the degree of whose attainment are lower than threshold levels, then evaluates the degree of anomaly. In next, he selects one of the following operations and decides how to cope with anomaly newly occurred.
(1) Operation for mitigating anomalous plant state
Based on the above mental model, he decides anomalous operation goals to be mitigated, then he decides operation components to be used and operation quantity to be moved.
(2) Operation for trip
He decides the timing of trip if needed.

III. EMERGENCY OPERATION SYSTEM BASED ON OPERATOR THINKING MODEL

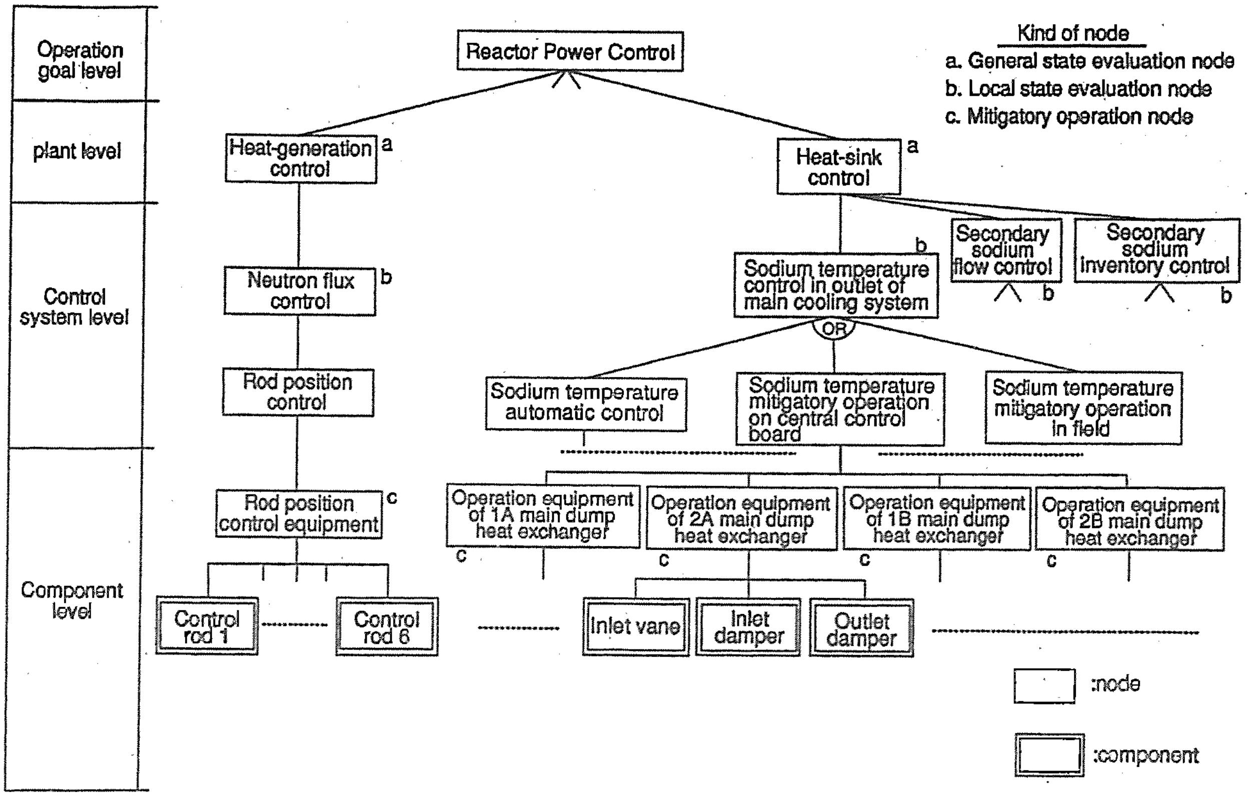

Figure 5. Partial example of operation goal network.

At first, the important knowledge base used in the emergency operation system is presented. In next, the functional constitution of this system is explained. Finally, the outline of the trial system is described.

A. Operation Goal Network

Operation goal network which corresponds to the mental model described in the preceding chapter is constructed based on operation manual and the function and structure data of a plant. It has a hierarchical structure, for nodes in upper levels show more general operation goals, on the other hand, nodes in lower levels show more concrete operation goals or means which attain more general goals. A partial example of a operation goal network whose object plant is "JOYO" and whose final goal is "reactor power control" is shown in Figure 5. This network is the important knowledge base of the emergency operation system. According to type of node, each node has some of the following information necessary to decide emergency operation.

(1) Information concerning own node, upper and lower adjacent node
(2) Information to evaluate the degree of anomaly and emergency in plant
(3) Information to calculate operation quantity
(4) Information to discriminate subsystem
(5) Information concerning operation component to be used.

B. Functional Constitution of Emergency Operation System

The functional constitution of this system is shown in Figure 6. It has a hierarchical structure which are composed of a plant monitoring system at the highest level and other subsystems at lower levels. The outline of the subsystems are as follows.

(1) Plant monitoring system

This system which is periodically activated monitors the state of a plant and decides whether emergency operations are to be carried out at once.

1) The degree of attainment of general state evaluation node is calculated according to the following steps.

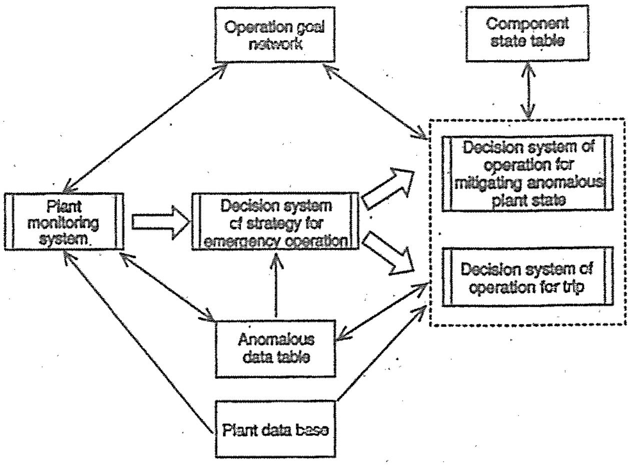

Figure 6. Functional constitution of emergency operation system.

a. The plant evaluation index which evaluates the state of a node is calculated.

This index is expressed by a function whose variables are plant data. For example, the state of node which shows "heat-sink control" is evaluated by the quantity of heat removal by a main dump heat exchanger. The quantity is calculated by multiplying a sodium flow rate by the difference between inlet and outlet enthalpy of a main dump heat exchanger.

b. The relative value x of plant evaluation index is defined as follows.

$$x=(x1-x2)/x2 \qquad (1)$$

x1: current value of plant evaluation index
x2: normal value of plant evaluation index

c. The function value f(x) is calculated using the state evaluation function shown in Figure 7.

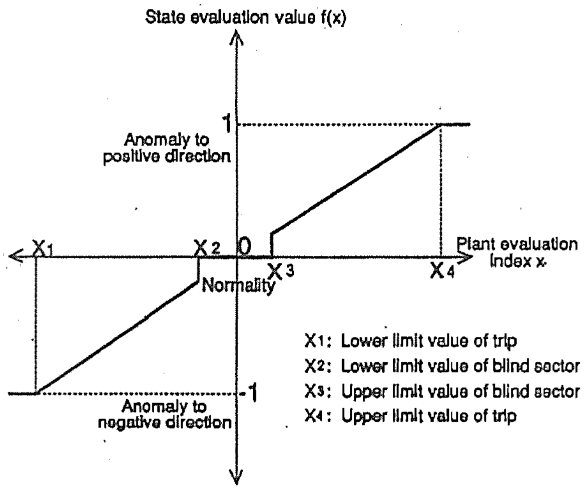

Figure 7. State evaluation function.

d. The degree of attainment DA is calculated by the following equation.

$$DA=1.0-|f(x)| \qquad (2)$$

2) Only if anomalous nodes are found, the degree of emergency is evaluated, otherwise, nothing is carried out until next calculation time.

3) Using rules which express the relationship between the degree of emergency and its influence factors, such as, the degree of attainment, its differential value, degree of importance and sensitivity to disturbance, the degree of emergency is estimated by fuzzy reasoning.

4) Based on evaluation results, it decides whether emergency operations are to be carried out at once.

(2) Decision system of strategy for emergency operation

This system decides the subsystem to be activated next from the following subsystems.

1) Decision system of operation for mitigating anomalous plant state

2) Decision system of operation for trip

Further, it decides how to cope with anomaly newly occurred.

(3) Decision system of operation for mitigating anomalous plant state

Based on plant data and operation goal network, this system decides operations for mitigating anomalous plant state in order to prevent a trip and maintain the safety of a plant.

1) Decision of operation component to be used

Using operation goal network, this system searches effective operations to mitigate anomalous plant state according to the following steps. Thereafter, it checks whether candidate operations satisfy given conditions and decides the operation to be carried out.

a. It starts searching from general state evaluation nodes indicating anomaly.

b. "AND" connection of operation goal network shows the relationship between an upper node and lower adjacent nodes all of that are required to be normal in order to attain the goal of an upper node. Because normal nodes are not necessary to be mitigated, mitigatory operation nodes are exist only under anomalous nodes. Therefore, it evaluates local state evaluation nodes and identifies anomalous subsystems which belong to these nodes. Finally, all flags which correspond to anomalous subsystems are changed from "off" to "on".

c. "OR" connection shows the relationship between an upper node and lower adjacent nodes all of that are alternative means to have the ability to attain the goal of an upper node. Mitigatory operation nodes are exist under all lower nodes which are available. All flags which correspond to available nodes are changed from "off" to "on". Thereafter, the preferential order of their nodes is decided using rules which are generated by operation manual and know-how.

d.Steps b. and c. are carried out for all nodes whose flags are "on", until mitigatory operation nodes are found.

2)Decision of operation quantity to be moved

For the combination of mitigatory operations which are most preferential, it decides operation quantity which can prevent a trip and maintain the safety of a plant by mitigating anomalous plant state. If suitable operation quantity cannot be found, different combination is tried repeatedly.

a. Identification of the combination of mitigatory operations which are most preferential

b. Decision of operation quantity

In order to mitigate anomalous plant states, the stepwise input functions Uj(t) of mitigatory operation node j(j=1~j max) must be decided so as to satisfy the following constraint equations for i=1~i max.

$$X_{imin} \leqq X_i(t) + \sum_{j=1\sim jmax} \sum_{k=1\sim imax} \delta_{i,k} \cdot U_j(t) \cdot S_{j,k}(t) \leqq X_{imax} \qquad (3)$$

t:Elapsed time from starting point
i:Number of local state evaluation node which is anomalous
j:Number of mitigatory operation node which is used for mitigating anomalous node
Sj,k(t):Operation influence function to node K by operation of minigatory operation node j(This function expresses the analog trend of the change of local state evaluation node K influenced by a stepwise operation of node j, when the plant is normal and in 100% power.)
Xi(t):Prediction function of plant variable which corresponds which anomalous node (This function is obtained by interpolating the past value of Xi and used for prediction of the future value.)
Ximin:Lower limit value which Xi must not violate in order to maintain the trip margin or plant safety
Ximax:Upper limit value which Xi must not violate
δ i,k:Sign which shows 1 if and only if i equals k, otherwise, shows o

c. Decision of detailed operation way

If operation quantity which satisfies Eq. (3) cannot be found,the above calculation is continued for different combination. Otherwise, detailed operation way is decided based on operation manual, available operation components and their preferential order, etc..

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3) Confirmation of results of operation

It confirms whether decided operations are carried out correctly.

(4)Decision system of operation for trip

Based on plant monitoring data, etc., it decides the timing of trip in case the degree of emergency of a plant increases so rapidly that it cannot decide suitable emergency operations.

C.Trial System

The trial system which has the above functions has been constructed. The outline of this system is as follows.

(1)Computer
1)Types of computer:SUN-4 workstation
2)Language:C-language
(2)knowledge base

The outline of the operation goal network which is the important knowledge base used in this system is as follows.

1)Number of node:25
2)Number of state evaluation function:10
3)Number of fuzzy function to evaluate the degree of emergency:50
4)Number of operation influence function:50
(3)Data base
1)Number of data composing plant data base:50
2)Number of data stored in anomalous data table:10
3)Number of data stored in component data table:50

Based on results of operation of this system, it has been clarified that it can decide emergency operations in real time.

IV. CONCLUSION

The operator thinking model was developed using the operator training simulator, then and the emergency operation system was constructed based on this model. Based on results of operation of this system, it has been confirmed that the method described in this paper is very effective in order to construct an expert system which can replace the reactor operator's role with AI system. Application of this model to developing an autonomous plant is intended by refining the model and programming other part of it.

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