Integrated method for constructing knowledge base system for proactive trouble prevention of nuclear power plant

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Abstract: Integrated method for constructing knowledge base (KB) system for proactive trouble prevention of complex machine system such as nuclear power plant has been studied in this paper. The new ideas employed in this study are: (i) Structuralizing trouble KB for trouble prediction and prevention, (ii) Realizing such KB by using web database, (iii) Modeling plant system by the combination of solid matters and non-solid matters, (iv) Modeling solid matters as object-oriented KB with the combination of structural components and electrical circuits, usage and environmental conditions and knowledge on troubles, and (v) Modeling non-solid matters by a revised Multilevel Flow Model (MFM). The framework is proposed on how to systemize those five different ideas on the basis of graphical modeling method by the revised MFM. A preliminary study is also conducted on applying the proposed method to a fast reactor prototype “Monju”, in order to reduce problems to be improved for the usage of revised MFM for real scale application for nuclear power plant.

Keyword: proactive trouble prevention; knowledge base system; multilevel flow model; Monju

1 Introduction

Nuclear power plant is a large-scale complex engineering system, and moreover it is a typical safety-critical system because it contains and deals with dangerous radioactive materials. Therefore, maintenance of safety is strongly requested by general public to the nuclear industry.

These days in Japan, nuclear industry assembles all trouble data occurred in all nuclear facilities and the collected trouble information are disclosed on the website called NUCIA [1]. On the other hand of information disclosure, the nuclear industry has been enforcing quality assurance activity, to diminish trouble occurrence by utilizing the collected trouble information. This has been the activity in connection with non-conformance management [2]. Furthermore, "failure knowledge database" project [3] has been in progress in Japan, by which many accident cases occurred in every industrial sector not to mention nuclear, are evaluated by experts and the evaluated information appear on the website of failure knowledge database as precious lessons.

On the other hand of trouble database, various methodologies such as FMEA [4], FTA [5], Living PSA [6] have been developed, and those methods have been extensively utilized for preventing recurrence of troubles.

The final goal of the authors’ presented study is to develop new computer-supported tools for the field workers in nuclear power plant who are at the front end to maintain safety of nuclear power operation. The concrete target of the tool development is to exploit new knowledge based systems to support field workers’ maintaining their expertise knowledge and skill by organizational learning.

The authors had investigated on the basic method on how to configure the knowledge based system for managing information on plant troubles systematically.

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The study has been conducted by literature survey in the field of quality management on plant maintenance [7, 8]. They have also considered on how to implement a functional modeling method called MFM [9] into the conceptual frame of the afore-mentioned knowledge based systemization, and they had reduced the modeling framework of the knowledge base system [10].

In this paper, the progress of the authors' knowledge based system development will be presented from the original proposition to configure the basic concept of the knowledge-based plant modeling by applying MFM model up to the preliminary study by applying it for a prototype fast reactor plant.

2 Exploring knowledge based support system for field workers

From the aspect of proactive prevention of trouble occurrence during plant operation, it is expected that the plant personnel can detect symptom of any anomaly occurred in the plant system, find its root cause and think over appropriate countermeasure well in advance to its progression into serious accident so that the operators have to shut down the plant. In order to enhance and maintain their risk management ability of plant operation and maintenance by their daily organizational learning, the following two computerized support are the subject of investigation in this study.

The one is (a) Web database in which three kinds of knowledge base (various failure mechanism, configuration of machine systems and usage of materials) are assembled so that they are easily accessible by many field workers over the internet. The other is (b) Interactive tool development for field workers to analyze troubles and generate and evaluate appropriate countermeasure to be used for maintenance work at the local worksite.

There are two fundamental questions to realize knowledge based system for proactive trouble prevention in the design and operation of the plant system. One is (a) how to do with "trouble information" (or how to model troubles which would occur in the plant") while the other, (b) how to model a target plant to be operated or maintained.

2.1 How to model troubles

There is a lot of trouble information to be effectively utilized to preclude repetition of failures. Therefore, a lot of trouble information database have been developed around the world. However, all the trouble information databases are not necessarily useful ones, and all the contents of fault event cases are not useful ones. In order for trouble information to be re-usable, it is necessary to re-structure the knowledge contents.

Structuralizing trouble knowledge should be based on segmentation, generalization and reduction of relations. A general knowledge base on trouble can be described as shown in Fig. 1, where the knowledge base is constituted by the two bases for (i) trouble prediction and (ii) countermeasures.

2.2 How to model target plant

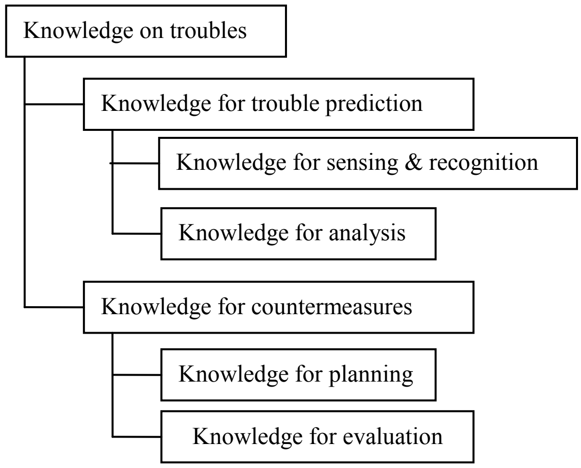


Fig. 1 Knowledge on trouble.

There are two types of object items to configure plant system. One type of the object items is solid matter which can be classified as structural element and electrical element. On the other hand, there are many

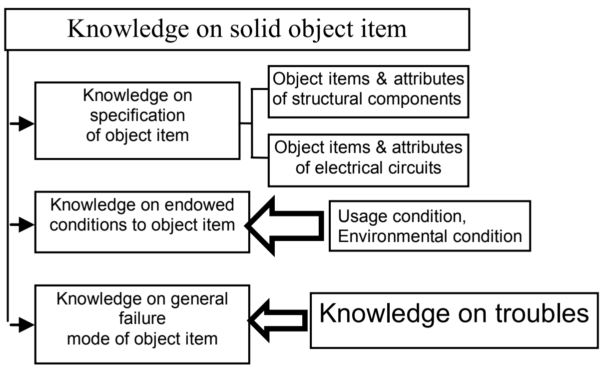


Fig. 2 Knowledge base for solid matter.

non solid matters such as fluid flow, gas flow, electric flow (electric current, electric power), and information flow (signal flow from sensors, to processors for control and safety purposes, and to actuators for automatic action or to displays for operators' manual processing).

2.1.1 Modeling solid matters

The concrete target of object items is machines or equipments such as pump, valve, reactor protection system, control system cabinet, *etc*, in the plant to be maintained by workers. The knowledge base for such solid matters (machine or equipment) can be described as shown in Fig. 2, where the solid objects are assumed to be the combination of structural components and electrical circuits with their design attributes as described by Fig. 3 and Fig. 4, respectively. In Fig. 2, it is also given two kinds of trouble related information to the target object item; (a) Knowledge on endowed conditions to object item (usage limitation, *etc*), and (b) Knowledge on general failure mode of object item.

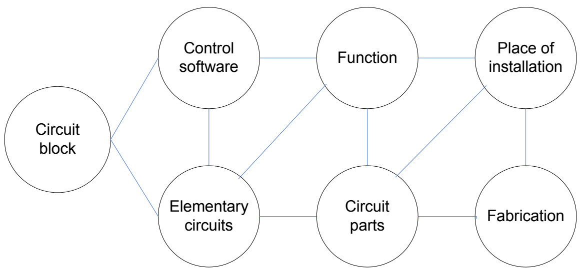


Fig. 3 Object items & attributes of structural components.

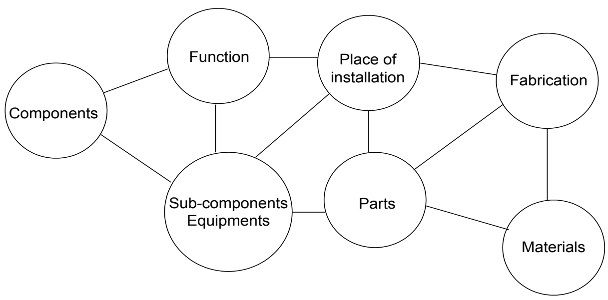


Fig. 4 Object items & attributes of electrical circuit.

2.1.2 Modeling non solid matters

Various flow elements running through the plant system are important to materialize the objectives of plant system. The flows of fluid and gas runs through many different components and parts composed by various solid matters will transport heat and energy converted by various physical and chemical reaction and the various forms of the product flows including electric flow (electric current, electric power) will also run through the plant. Moreover various information run through the control and safety systems as signal flow from various sensors, to processors for control and safety purposes, and to various actuators for automatic action or to displays for operators' manual processing. Those various flows are important to realize and maintain the function of the plant system. The problem of modeling non solid matters is how to describe those various flow running through the plant system with correlating with their meaning in terms of functions to be realized.

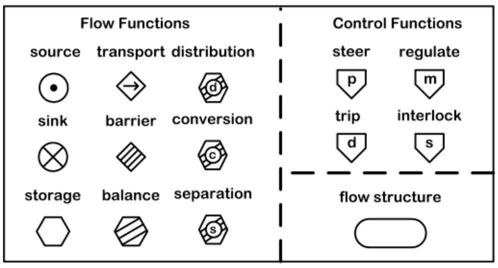
To do this, a revised multilevel flow model (MFM) will be used which also takes into account of the role of control system in the plant to describe those flows of "Energy, mass and control information" in a machine system with respect to goal and means relationship [11]. The MFM model is a graphical method to describe the semiotic meaning of various process systems. Figure 5 shows the symbols used in the revised MFM: Those related with flow function, control function and flow structure in (a), while those related with means-end relations, control functions, causality and objective and goal in (b).In the original MFM model [9] the semantic meanings of various flows of mass, energy and information in the process system are described by various symbols of functions with flow structure in Fig. 5 (a) , while those of means-end relation and objective and goal relation in Fig. 5 (b). By using this original MFM model, various application studies have be conducted to develop various tools for fault detection, signal validation, *etc*., but the revised MFM model has the potential to expand its semantic modeling to the failure in the machine system which has various control and safety functions. [11]. The essential points of the revised MFM model are summarized as the two points; (i)Process functions are represented by *elementary flow functions* interconnected to form flow structures *representing* a particular *goal oriented view* of the system, and (ii)MFM is founded on *fundamental concepts of action:* each of the elementary flow and control functions can be seen as instances of more generic action types[11].

Various flows of "Energy, mass and control information" are important to understand the nature of troubles occurred in the machine system from the following aspects: (i)Where and by what way the various useful functions of the machine are implemented, (ii)By what way such useful functions will be disabled in a certain trouble case, and (iii)What kind of unexpected function or adverse effect will be brought about to the system.

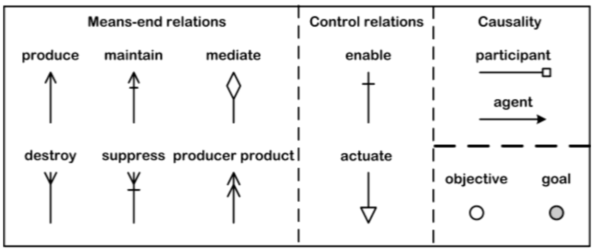
However it should be pointed out that in the usage of revised MFM for modeling the target plant, the derived MFM model should be further combined with the whole data of Object items & attributes of solid matters as stated in 2.1.2 as well as by Fig. 2.

By usage condition, environmental conditions and the knowledge on troubles of solid matter in Fig. 2, you can reason where, why and how the intended function of the process system is destroyed.

In the succeeding Chapter 3, we will first show how to realize knowledge base on trouble for various solid matters as a web database.



(a) Flow function, control function and flow structure



(b)Means-end relations, control functions, causality and objective and goal

Fig. 5 Symbols used in revised MFM model.

3 Web database

A machine trouble knowledge database has been developed as free accessible database as a web contents in the website of Symbio Community Forum [12]. This is an interactive database which is composed by the following five knowledge bases of broad engineering areas.

(i) Knowledge base on troubles commonly applied for various machines. Concretely, this is the condensed knowledge on various relationship data on stress, failure mechanism, and hazard-failure-damage mode versus trouble detection-evaluation-countermeasure, which is based on the authors' proposed method [10] as shown in Fig. 1.
(ii) Database of failure cases
(iii) Database of nuclear facility/system/component (database of reactor type and database of equipments and parts common to any reactor type)
(iv) Database of materials as classified by the difference of usage
(v) Thesaurus of terminologies for keyword retrieval.

The above web contents have been programmed by Wikimedia software used in free electronic encyclopedia called Wikipedia which is prevailing around the world [13]. Therefore, user can easily create, modify and improve the contents of the online database by collecting the information which they want from the abundant information sources they can access freely by WWW (world wide web).

The field workers of nuclear power plant will be able to develop the web database which is specific to their own plant by their own activity.

4 Knowledge-based plant model

As already mentioned in **2**, the modeling of target plant system will be treated separately: for the part of solid matter while for the part of non solid matter by using the revised MFM. In this chapter, the detailed description of the solid matter parts will be discussed first, followed by the preliminary study by the revised MFM on how to treat both control and safety systems which are important to the operation and maintenance of nuclear power plant.

4.1 Detailed description of solid matter items

This is how to describe the three knowledge bases for various facilities, systems and components in the nuclear power plant as shown in Fig. 2. You can utilize the web database mentioned in **3** to describe various elements for the three knowledge bases by the following ways:

(i) Knowledge on specification of object item

In case of structural component, Information on Function, Sub-components, Equipments, Place of Installation, Parts, Fabrication, and Materials will be afforded for a certain component (see Fig. 3).In case of electrical circuits, knowledge bases are generated similarly by seeing Fig. 4.

Detailed modeling by the above way will be made for object items lower than the equipment level. And for the generation of knowledge objects higher than equipment, *i.e.,* from equipment to system, from system to facility, the knowledge base of the object item of the higher level will be described by the combination of those of lower level object items.

(ii) Knowledge on endowed conditions to object item

The restricted conditions of usage, *i.e.,* operating condition, environmental condition, *etc.,* will be described in accordance with the level of equipment, system, and facility.

(iii) Knowledge on general failure mode of object item

Knowledge for trouble prediction (Knowledge for sensing and recognition, Knowledge for analysis), and Knowledge for countermeasures (Knowledge for planning, Knowledge for evaluation) as given by Fig. 1, will be afforded for the levels of facility, system, and equipment, and even much lower level of parts.

4.2 Control systems viewed from action theory

The revised MFM is based on action theory proposed by Von Wright. [14]. According to M.Lind, the logical definition of concept of action is based on concept of change. Change is a temporal succession of two states represented by the schema pTq, where p: proposition which is true before the change, T: temporal operator (Then), q: proposition which is true after the change, and $\neg p$: negation of proposition p.

However an action is not only a change in state of affairs but also it has a counterfactual aspect because the change would not occur unless the action was done. A logical definition of an action must also refer to the hypothetical (not actualized) state of the world that would obtain if the action was not done. In this way, action can be defined by the schema $pTqIr$ where I (instead) is an operator relating the actualized state q with the hypothetical state represented by the proposition r.

According to Von Wright, human action can be classified into the elementary action types as listed in Table 1, where active human behaviors work as "intervention", while passive ones as "omission".

Table 1 Von Wright's elementary action type

Type	Description	Schema
Intervention	Produce p	$\neg p\ TpI\neg p$
	Maintain p	$pTpI\neg p$
	Destroy p	$pT\neg pIp$
	Suppress p	$\neg pT\neg pIp$
Omission	Let p happen	$\neg pTpIp$
	Let p remain	$pTpIp$
	Let p disappear	$pT\neg pI\neg p$
	Let p remain absent	$\neg pT\neg pI\neg p$

This concept can be used for manual action by human worker in the nuclear plant. While M. Lind classified the elementary control functions by MFM as shown in Table 2. In M. Lind's view, the control actions are caused not only manual actions but also automated machines. In Table 2, there are four kinds of tasks, *i.e.*, steering, regulation, tripping and interlocking, but he classified two types of "promotive" and "oppositive" by the difference of "purpose", although the four kinds of tasks are identical by the forms of scheme. To be concrete, the type of promotive is given by control systems while oppositive by safety system in case of process systems such as nuclear power plant.

Table 2 Elementary control functions in MFM (by M. Lind)

Type	Task	Purpose	Schema
Promotive (Control system)	Steering	Ensure p is produced	¬p Tpl¬p
	Regulation	Ensure p is maintained	pTpl¬p
	Tripping	Ensure ¬p is produced	pT¬plp
	Interlocking	Ensure p is suppressed	¬pT¬plp
Oppositve (Safety system)	Steering	Ensure ¬p is destroyed	¬p Tpl¬p
	Regulation	Ensure ¬p is suppressed	pTpl¬p
	Tripping	Ensure p is destroyed	pT¬plp
	Interlocking	Ensure ¬p is maintained	¬pT¬plp

The various facilities, sub-systems and equipments to control the whole plant system are largely machines of electric circuit as depicted by Fig. 3. And those various machine elements to control the whole plant system should be described as the object-oriented knowledge base system by clarifying their task and purpose of individual control elements as given by Table 2.

5 Preliminary case study

5.1 Description of Monju plant

The word “Monju” means Japanese fast breeder reactor prototype which had stopped operation by sodium leak accident since December 1995 until its restart in May 6, 2010. This reactor is rather small electrical output of 280 MWe at full power but the plant configuration is rather complex and peculiar to be compared with the conventional light water reactor. The reactor fuel is mixed oxide pellets with stainless steel cladding, and reactor coolant is liquid sodium. The plant is composed by three different loops. The reactor power generated in reactor core is transferred by liquid sodium flow in the primary loop. The conveyed heat in the primary loop is then transferred to also liquid sodium flow in secondary loop through the intermediate heat exchanger. The conveyed heat by the secondary sodium flow is transferred to water flow in the ternary loop by rather complex configuration of water passage route of super-heater, steam separator, evaporator, turbine, condenser, as well as air ventilation path and many bypass route of steam by the manipulation of many valves. The P & ID diagram of FBR is more complex than light water reactor with many loops, components, pipes and valves, *etc*, and many feedback control systems.

The operation procedure starts from attaining the zero critical state, then to warming up the water loop to cool by feed water, to heating up to 40 % power, then approaching to full power. You cannot see through the reactor and sodium loops because of “liquid sodium”. So you rely on many sensors suited for sodium environment for early fault detection and safety operation. You have to avoid any occurrence of sodium leakage in the plant. And many robotics will be employed for both regular shutdown testing and repair and in-service inspection.

5.2 Modeling Monju plant by MFM

There are a lot of subjects in Monju plant for the authors to apply the methodologies proposed in this paper. The authors have initiated how to describe the whole Monju plant effectively by using MFM. The starting point of reducing MFM diagrams is the illustration of whole plant control systems of Monju plant as given in Fig. 6 [14].

In Fig. 6, the heat transport loops of primary sodium, secondary sodium and ternary water-steam loop are only depicted as a single loop, although as a matter of fact there are three similar loops in parallel for those primary, secondary and ternary loops. There are six control systems in Monju plant as shown in Fig. 6.

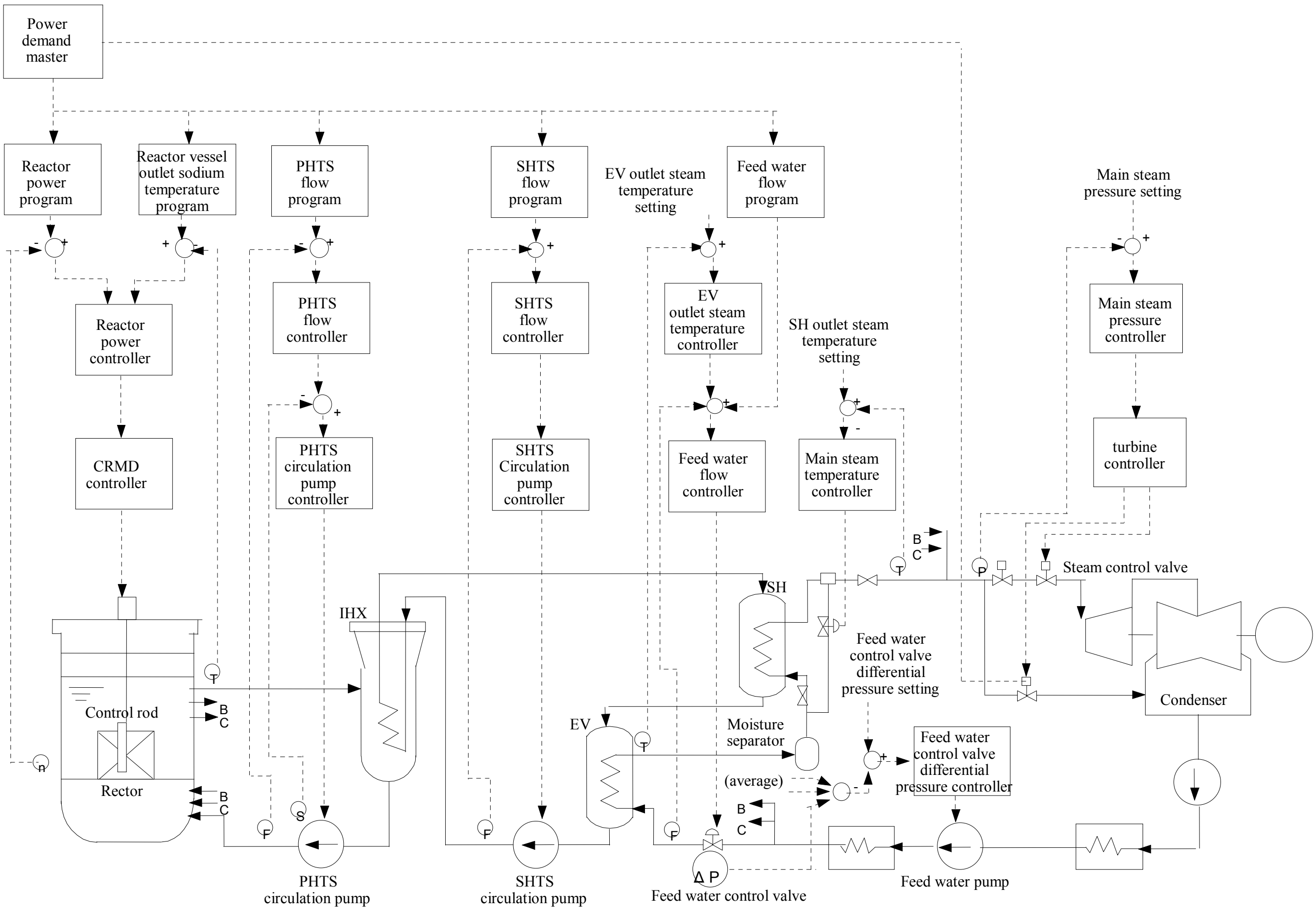


Fig. 6 Whole control system of Monju plant.

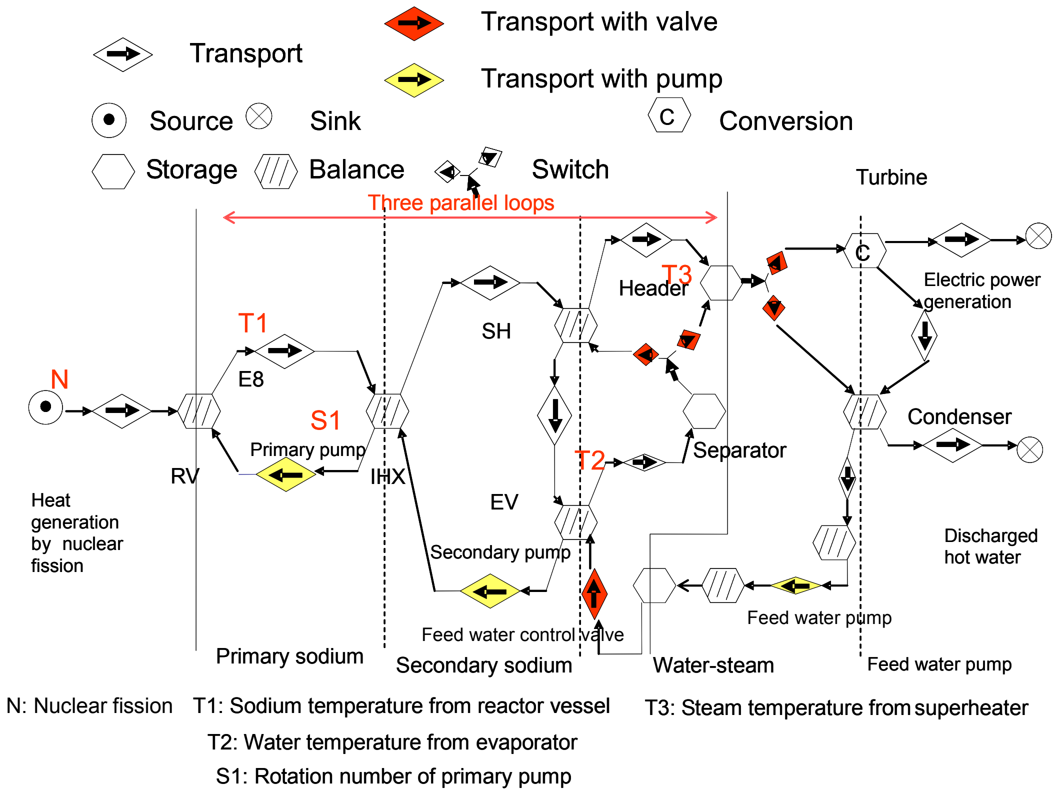


Fig. 7 Energy flow diagram of Monju.

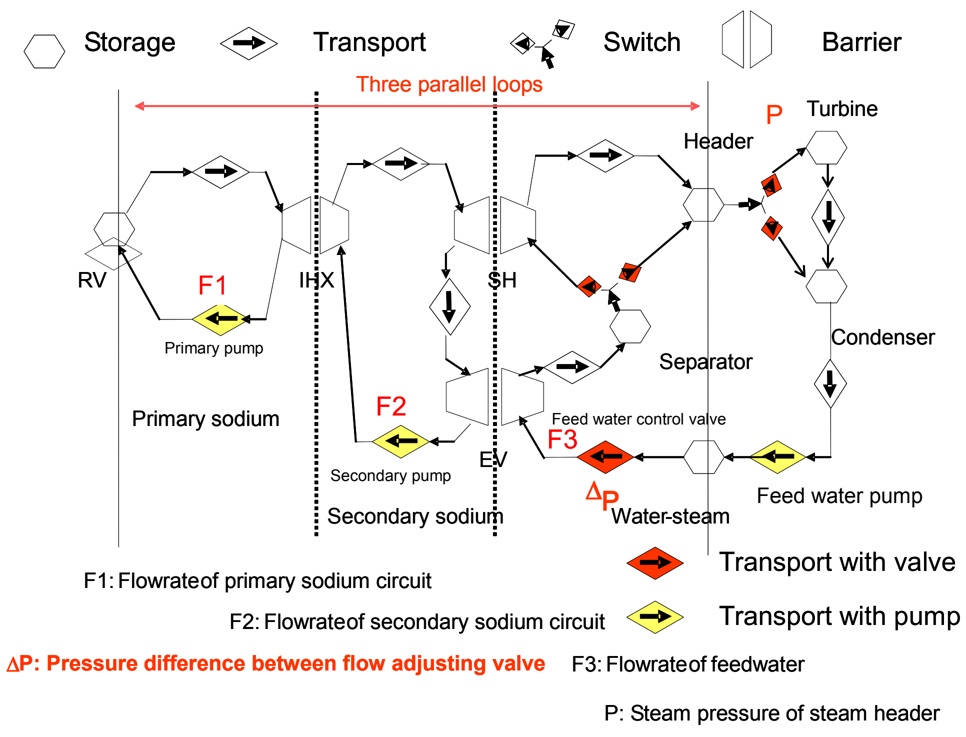


Fig. 8 Mass flow diagram of Monju.

They are (i) reactor power control system, (ii) primary main coolant flow rate control system, (iii) secondary main coolant flow rate control system, (iv) feed water flow rate control system, (v) main steam temperature control system and (vi) main steam pressure control system. But there are no safety related systems included in Fig. 6, such as reactor containment, guard vessel, inert gas control system, *etc*.

Based on this rather simplified illustration of the Monju plant, the MFM diagrams of Monju plant can be drawn as Figs. 7 and 8, respectively for energy flow and mass flow, where the authors tried to use various symbols listed in Fig.6 for the revised MFM

As you see from the both of Figs. 7 and 8, the used symbols of MFM model are almost similar to the original symbols as listed in Fig. 5, but a new symbol of "switch" should be introduced to describe the configuration change of valve alignment pattern of open/shut in accordance with the change of plant operational mode in water-steam loop. The symbol of "barrier" is somewhat changed in Fig. 8 in order to distinguish the difference of loops by the barrier functions of intermediate heat exchanger (IHX), super heater (SH), and evaporator (EV). In Figs. 7 and 8, the location and the kind of process instrumentation of Monju plant are also indicated by red color.

Concerning the action types of control systems, five

Table 3 Summary of major control systems in Monju

Control System	Control Targets	Objective	Nature of task
Primary main coolant flow control system	Primary sodium flowrate	Set flowrate to meet power demand	Steering
Secondary main coolant flow control system	Secondary sodium flowrate	Set flowrate to meet power demand	Steering
Main steam temperature control system	SH outlet steam temperature	Maintain preset value of main steam temperature	Regulation
Main steam pressure control system	Main steam pressure	Maintain preset value of main steam pressure	Regulation
		Detect main steam pressure rise by load drop to open bypass valve	Regulation

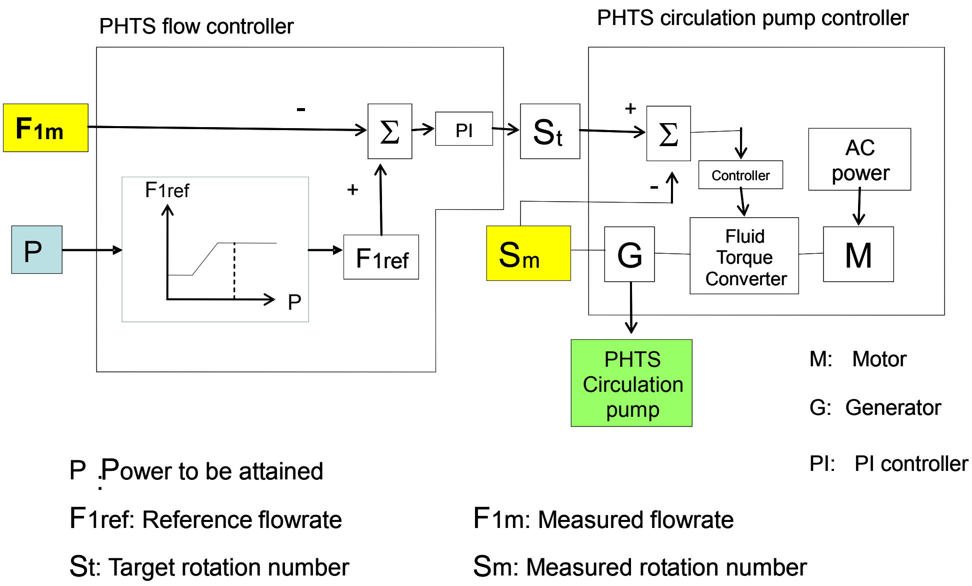


Fig. 9 Block diagram of primary main coolant flow control system.

control systems of Monju plant as appeared in Fig. 6 are classified as shown in Table 3, for control target, objective and nature of task. This kind of summaries of individual control system would be useful to make the knowledge bases of control systems.

Out of the five control system in Table 3, the rather detailed configuration of the first two control systems of primary and secondary sodium coolant flow are shown in Figs. 9 and 10, respectively. From the both figures you can see how the flow rate of both the primary and secondary loops are regulated to the desired flow rate to meet with the target value of reactor power. You can also see that the both controllers are similarly composed by two elementary parts from the both figures, while the flow control of sodium pumps is different with each other: the pump used in the primary loop is motor-generator set, while the secondary loop by inverter for changing the pump speed. There would be a certain reason why different control methods are used, how they are comprised and what will happen if any of these fails by what

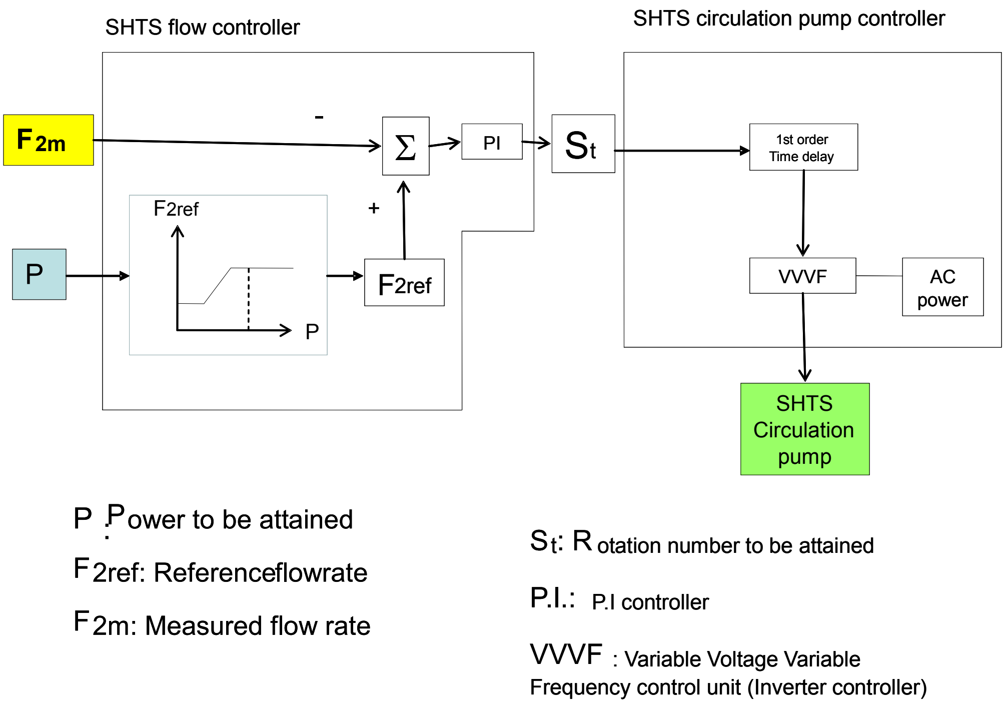


Fig. 10 Block diagram of secondary main coolant flow control system.

mechanism of failure. If those information are put in those diagrams individually and stored in a database, these will become knowledge bases of the targeted Monju plant model.

5.3 Discussion on plant model by MFM

Both the diagrams of energy flow and mass flow as depicted in Figs. 7 and 8 are convenient to understand the complicated system configuration of Monju plant, and the roles of various equipments comprising the plant. And also from Figs. 9 and 10 of the control system block diagrams you can see how the sensors are allocated to measure various process parameters to monitor and control the plant behavior. The names of major components to comprise the plant are indicated in Figs. 7 and 8, and if you implement the pop up menu to see the part of those names you can see the structure, specification and the trouble knowledge of the equipment. This will become a good visualizing basis for the plant workers to get useful knowledge base for proactive trouble prevention.

However, the diagrams of energy and mass flows used in this study as a MFM model for Monju plant is rather simplified by omitting three loop configuration, *etc.*, as well as no consideration on safety systems. Concerning the plant control systems, the shown two block diagrams are good example how the plant model of solid matters (pump, valve, *etc*) and non-solid ones (sodium flow) will be correlated with control system and that the control system will be configured by lower level circuit, *etc.*, to organized a certain control function.

In the next step of this preliminary study, the authors would like to add the block diagrams of the other control systems in the plant, and the applicability of the revised MFM model will be studied for the who plant control program which deals with the start up the plant, reactor power increase for electric power generation until normal power operation, and vise versa.

6 Concluding remarks

The objective of this study is to propose a new integrated method of knowledge base system for proactive trouble prevention. In this paper, The new ideas employed in this study were (i) Structuralizing trouble KB for trouble prediction and prevention, (ii) Realizing such KB by using web database, (iii) Modeling plant system by the combination of solid matters and non-solid matters, (iv) Modeling solid matters as object-oriented KB with the combination of structural components and electrical circuits, usage and environmental conditions and knowledge on troubles, and (v) Modeling non-solid matters by a revised Multilevel Flow Model (MFM). The central idea was the object oriented knowledge base by the application of revised MFM for the plant system which includes control and safety functions,

And the utilized integration method how to systemize those five different ideas was based on a graphical modeling method by the revised MFM.

A preliminary study is also conducted on applying the proposed method to a fast reactor prototype “Monju”, in order to reduce problems to be improved for the usage of revised MFM for real scale application for nuclear power plant. The authors proposed several additional symbols to describe the control system functions in the real control systems used in Monju control systems.

Conclusively, the proposed method was applied for Monju plant to test the applicability of MFM from the semiotic aspect. However at this stage, no consideration has been made on the semiotic analysis of the automatic system which is the specific feature of the revised MFM modeling.

In future, the authors would like to extend MFM modeling for the whole plant control systems as well as for the safety systems, by applying the revised MFM model for the effective representation of control and safety systems to meet with the practical need of providing field workers with a new tool of a lot of possibility for proactive trouble prevention.

Acknowledgement

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