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Functional Modeling of Nuclear Power Plant Using Multilevel Flow Modeling Concept

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Abstract

Because of limited resources of time and information processing capability during abnormal situation, diagnosis is difficult tasks in nuclear power plant (NPP) operators. Moreover since minimizing of adverse consequences according to process abnormalities is vital for the safety of NPP, introducing of diagnosis support systems have particularly emphasized. However, considerable works to develop effective diagnostic support system are not sufficiently fulfilled because of the complexity of NPP is one of the major problems. To cope with this complexity, a lot of model-based diagnosis support systems have considered and implemented worldwide. In this paper, as a prior step to development of model-based diagnosis support systems, primary side of pressurized water reactor is functionally modeled by multilevel flow modeling (MFM) concept. MFM is suitable for complex system modeling and for diagnosis of abnormalities. Furthermore, knowledge-based diagnosis process of NPP operator could be supported because this diagnosis strategy can represent operator's one.

I. Introduction

It is well perceived in the nuclear industry that provision of operator support systems is helpful for enhancing the operational safety of nuclear power plants (NPPs). Therefore, significant works have been widely performed to improve the operator's performance using operator support systems that assist operator by selecting or integrating of process data, identifying plant states, diagnosing abnormalities and prioritizing operation goals with respect to their importance. Among them, diagnosis support systems are particularly emphasized because minimizing of adverse consequences according to process abnormalities is vital for the safety of NPP, and because diagnosis of abnormalities is difficult tasks in operators due to their limited resources of time and information processing capability, during abnormal situation[1]. Therefore, the methodologies that can ascertain abnormalities from process data (i.e., indicators or alarms) are essential part in development of diagnosis support systems. Over the past decades, various diagnostic methodologies, such as event-, process-oriented and model-based approaches have been researched. However, the event- and process-oriented approaches are very hard to construct or modify because of its inherent complexity and inflexibility. Therefore, the activities to use model-based methodologies for diagnosis support system are increasing because these approaches can describe complex systems with logical and simple ways.[2]

In this paper, as a prior step to develop model-based diagnosis support systems, primary side of pressurized water reactor (PWR) is functionally modeled using multilevel flow modeling (MFM) concept. MFM is one of the functional modeling methodologies and is suitable for complex system modeling. In addition, implementation of diagnosis support system is relatively easy because physical systems or components are directly linked with its goals and functions in hierarchical manner.

II. Multilevel Flow Modeling

MFM that has been developed by M. Lind.[3] and that has the purpose to model a system as an artifacts, i.e. as man-made purposeful system. The major features of MFM that are main motives for selection of MFM to model NPP are as follows.

II.1 Suitable for complex system modeling

Various functions of plant system could be represented by a set of mass and energy flow on several levels. The basic dimensions of MFM are depicted in Fig. 1. A system is described in terms of goals, functions and the physical components along the means-end axis. At the same time, each of these descriptions can be given on different levels of decomposition along the whole-part axis. This means that MFM is suitable for modeling of complex systems because MFM can represent a system by a multiple descriptions on different levels of abstraction (whole-part). In addition, MFM can represent the context sensitivity of goal or functional descriptions because goals or functions could be described differently according to various abstraction levels. Therefore, MFM departs from modeling methodologies that based only on knowledge about the physical phenomenon of the system (i.e., shallow knowledge). The context sensitivity due to abstractions will be explained again in Sec. III.2.

II.2 Primitive functions

The most distinctive feature of MFM is the use of a set of primitive functions that are related with the mass and energy flow of system. The primitive functions and its meanings are shown in Table 1. Using these primitive functions, not only shallow knowledge but deep knowledge of complex systems can be represented effectively. Furthermore, these kinds of knowledge representations are useful for diagnosis of system.

II.3 Means-End relations

The system goals or functions that are represented by primitive functions are combined into a multilevel flow structure using means-end relations. In MFM, there are two types of means-end relations, called achievement (A) and condition (C) relation, actually. Achievement relation is used to represent the relation between a goal and function provided for its achievement. In other words, a goal can be achieved when some related functions are normally operated. In contrast to achievement relation, condition relation are used to represent the relation between a function and goals i.e., normal operation of function is affected by the achievement of related goals.

II.4 Consideration of operator's diagnosis strategy

To support a knowledge-based diagnosis process of operators, diagnosis support systems should provide information that accord with operator's thinking process. In case of model-based approaches, this means that diagnosis strategy should be similar with operator's strategy. From analysis of the cognitive task characteristics of operators in emergency condition, mass and energy balance that can be easily represented with flow structures of MFM are frequently used to narrow diagnosis domain down.[4] In addition, similar research mentioned that MFM can provide operator with helpful information for diagnosis.[5]

III. MFM for Functional Modeling of Nuclear Power Plant

Based on the above reasons, MFM is selected for functional modeling of NPP. From now on, the modeling sequences using MFM will be discussed.

III.1. System description using goals and functions

To model existing system using MFM, all systems should be described and divided in terms of its own goals and functions. For example, one of the most important goal of reactor coolant system (RCS) of PWR is heat transfer from reactor (Rx) to steam generator (SG). This goal could be accomplished when some sub-goals, such as "maintain RCS coolant inventory" and "maintain RCS coolant circulation", are satisfied. From these descriptions, chemical & volume control system (CVCS) and reactor coolant pump (RCP) could be considered, since CVCS and RCP are related to maintenance of RCS coolant inventory and maintenance of RCS coolant circulation, respectively. Furthermore, some functions, such as "provide stable coolant charging" and "provide stable coolant letdown" should be satisfied to maintain RCS coolant inventory, and these functions could be related to charging and letdown system, respectively.[6] In this manner, primary side of PWR could be divided into sub-systems that have specific goals or functions, until they are directly connected with certain components. Fig. 2 shows an example for means-end relations between goals and functions of RCS, and Fig. 3 shows RCS and its sub-systems that are partitioned according to sub-goals.[6]

III.2. Mapping of physical systems onto primitive functions

After system is partitioned into sub-systems, each sub-system could be represented with flow structures that consist of primitive functions of MFM. For example, flow structures to represent goal of RCS ("maintain heat transfer from Rx to SG") and its sub-goal ("maintain RCS coolant inventory") are shown in Fig. 4. Here, mapping criteria that give some guidelines to turn physical systems or components to primitive functions of MFM are summarized in Table 2. It is noted that these criteria could be decided differently according to context dependency of goal or functional ascription. For example, CVCS is in itself a fairly complex system provided for the management of the coolant inventory or boron content in RCS. But as seen with the abstraction level of achieving the heat transfer goal, its purpose could be considered as single storage function because the amounts of letdown and charging of coolant are not equal. Therefore, careful selections of mapping criteria with respect to abstraction levels are very important point for modeling.

To complete MFM representation, all flow structures should be interconnected by means-end relations and Fig. 5 shows an example of MFM representation for RCS.

III.3. Diagnostic strategy using MFM

Let consider when the goal, for example "maintain heat transfer from Rx to SG", is violated. This violation is detected by a set of process data (i.e. indicators or alarms) that could notify the change of RCS coolant inventory. After detection, an achieve relations (A) are used to find doubtful flow structures. That is, the flow structures interconnected with violated goal are selected along achieve relations. Then primitive functions in each selected flow structure are tested by process data, since each primitive function has its own values or status for normal operating conditions. Again, after some primitive functions that keep apart from normal condition could be selected, a condition relations (C) are used to find doubtful supporting goals. The violation of supporting goals could be identified by process data, and these searching will be continued until root causes of process deviation are found. This strategy is shown in Fig. 6.

IV. Results and Further Works

This paper has described a plant modeling method using multilevel flow modeling (MFM). It is shown that the MFM concepts facilitate the representation of complex plant. The most distinctive feature of MFM is the use of primitive functions that are related with the mass and energy flow of system. Especially, this type of modeling is useful for diagnosis and helpful for objective and consistent representation of system. To represent primary side of PWR using MFM, mapping criteria that give some guidelines to convert physical systems or components to primitive functions of MFM are suggested. Based on the diagnosis strategy described here and MFM representation of primary side of PWR, diagnostic support system are currently under implementation to ascertain ISLOCA accident. On the other hands, these mapping criteria will be used to represent knowledge-based decision behavior of NPP operators. As mentioned earlier, to decrease an operator's cognitive workload, information that are congruent with the operator's thinking process should provided by diagnosis support systems. From analysis of the cognitive task characteristics of operators in emergency condition, mass and energy balance are frequently used to narrow diagnosis domain down. Since these thinking processes can be easily represented using MFM, diagnosis support systems using diagnosis strategy of MFM would provide helpful information for knowledge-based diagnosis of NPP operators.

V. Reference

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Table 1. Primitive Functions and Its meanings

Function	Mass	Energy	Meaning
Source	●	⊙	• Infinitive source of mass or energy
Sink	●	⊗	• Infinitive drain (sink) of mass or energy
Transport	◆	◇ (with arrow)	• Either mass or energy can move through this function
Barrier	◆	◇ (hatched)	• An obstacle which is intended to prevent flow of mass or energy
Balance	⬢	⬡ (hatched)	• A function that can distribute or branch mass or energy flow
Storage	⬢	⬡	• An accumulator of mass or energy
Relations	—— A ——		• A goal can be achieved when sub-functions are satisfied
	—— C ——		• A function can be normally operated when sub-goals are satisfied

Table 2. Mapping Criteria between Primitive Functions and Physical Systems or Components

Function	Characteristic	Example
Source	• A devices that can generate or deliver mass or energy	• Rx core (energy)
Sink	• A devices that can account for a sink of mass or energy	• Sea water (energy)
Transport	• A devices that can transport mass or energy without loss • The amounts of input and output are equal	• Valve, Piping (mass) • Hx tube (energy)
Barrier	• A devices that can prevent from transporting mass or energy	• Hx tube (mass)
Balance	• A devices that can distribute mass or energy flow with intended ratio • The amounts of input and output are equal	• Hx, T-joint (mass) • Hx (energy)
Storage	• A devices that can contain or accumulate mass or energy • The amounts of input and output are not equal	• RCS, CVCS (mass) • Rx vessel (energy)

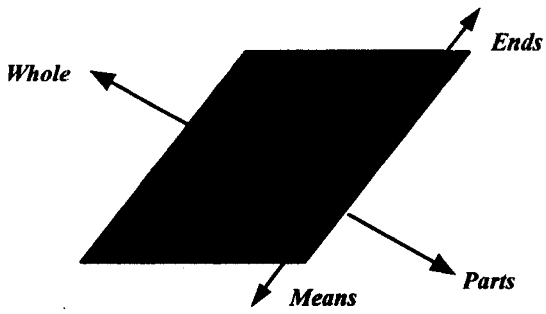

Fig 1. The Basic Dimensions of MFM

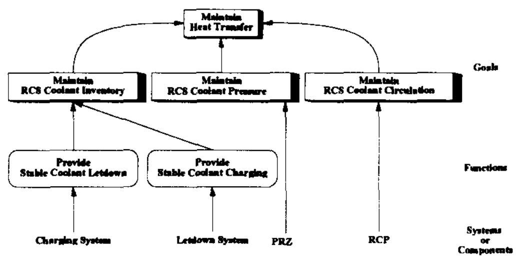

Fig. 2 Means-End relations for RCS

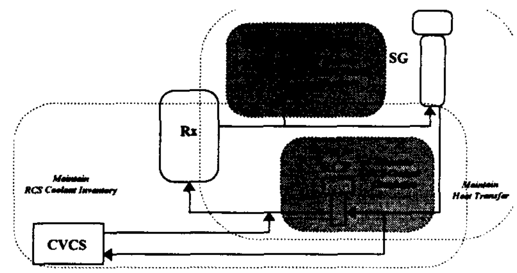

Fig. 3 Partitions of RCS according to sub-goals

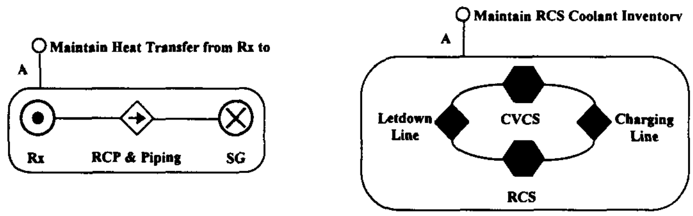

Fig. 4 An example of MFM representations with respect to specific goals

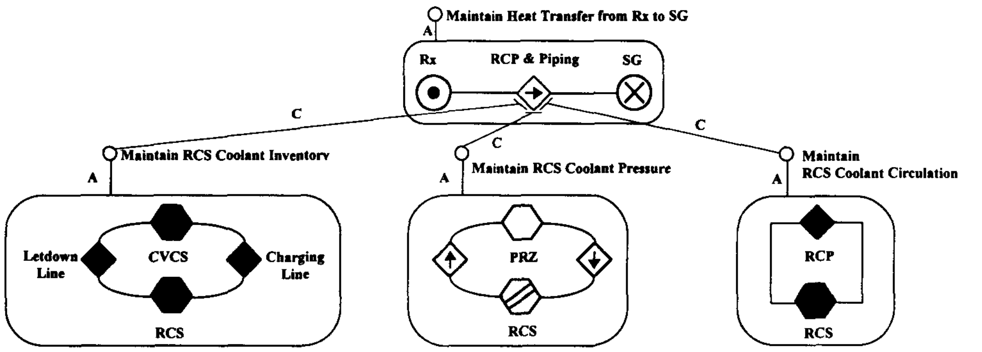

Fig. 5 An example of MFM structures that are interconnected with means-end relations of Fig. 2.

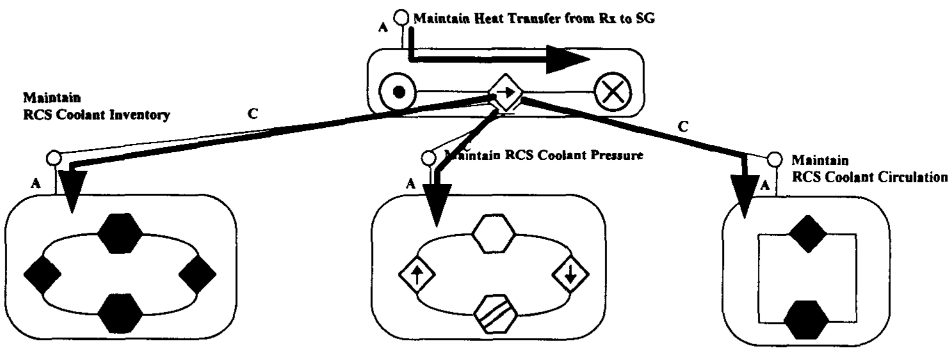

Fig. 6 Diagnosis strategy when MFM structures are constructed.