Functional modeling for operating procedure tasks of a Chemical and Volume Control System in PWR

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Abstract: Most of operator tasks in the nuclear power plants (NPPs) are performed by following a set of prescribed procedures, where human errors might occur in any phase of procedure. With the introduction of more operational information and automation into the main control rooms by digital technologies, operators are becoming easier to lose their position perception in the procedures and situation awareness when they execute operations. By employing Multilevel Flow Modeling (MFM), a strategy is presented for improving situation awareness and information sharing among operators when they implement operating procedures. Taking the Chemical and Volume Control System (CVCS) in PWR as an example, the procedure tasks of restoring CVCS operation from malfunctions are analyzed firstly, and then MFM models of CVCS in different task phases are presented. Finally, the potential applications are discussed of the proposed technology for emergency operating procedures management, human influence analysis and system reliability monitoring .

Keyword: operating procedures; human errors; Multilevel Flow Modeling; phased tasks

1 Introduction[1]

In process systems like Nuclear Power Plants (NPPs), most of operational tasks are performed by following a set of procedures that are plans of action to be conducted in a certain order or manner in normal and emergent situations. Human errors may occur in any phase during the performance of the procedures due to a variety of reasons. Engineering experience indicates that most incidents and accidents at NPPs can be eventually attributed to human errors, where the quality of interactions between human and machine plays a critical role in mitigating or deteriorating accidents [1].

As the Information Technologies (IT) has been introduced into human-machine system, the operational environment of Main Control Rooms (MCRs) in NPPs has being changed from analog to digital. New man-machine interfaces such as large display panels and computerized procedures have been widely adopted in most of the new installations of NPPs [2]. On the one hand, the more operational information being provided to operators through computer-based interfaces, the greater advantage for the operators in monitoring the system situation from a wide perspective more effectively. On the other hand, the keyhole view through computer screen can severely limit information processing and increase cognition load of operators [3]. Furthermore, high level of automation makes operators much more easily lost their position perception in the procedures and situation awareness. One of suggested means of improving situation awareness is information sharing and coordination between the operators in MCRs to make them well informed about the system operating status and to facilitate communications among the operators. Explicit knowledge representation of plant by a common modeling method can be deemed as one of the effective methods to serve this purpose [4].

Multilevel Flow Modeling (MFM) is a functional modeling method of complex industrial processes [5]. The relation of means-end as well as whole-part decomposition and aggregation play the foundation in MFM. In the dimension of means-end, MFM describes how a complex process system provides the means to serve its design purposes. At the same time, each of these descriptions can be given on different levels of whole-part decomposition. These concepts of MFM enable humans to cope with complexity and give the reasoning power on various levels of abstraction. The various graphical elements of MFM are shown in Fig.1. A detailed introduction on the concepts of MFM and the description of modeling

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examples are presented in [5] and [6]. MFM has been used to represent a variety of complex dynamic processes such as nuclear power plant [7]. MFM is not only a powerful tool of knowledge representation, but also effective as knowledge-based reasoning method. Especially the MFM is useful for cause-consequence reasoning. In this respect, It has been applied for a variety of purposes ranging from root cause analysis[7], alarm design[8] and alarm filtering [9], to reliability analysis[10] and risk monitoring[11-12], for various safety critical systems including NPPs, oil and chemical industries, *etc.* [13-14].

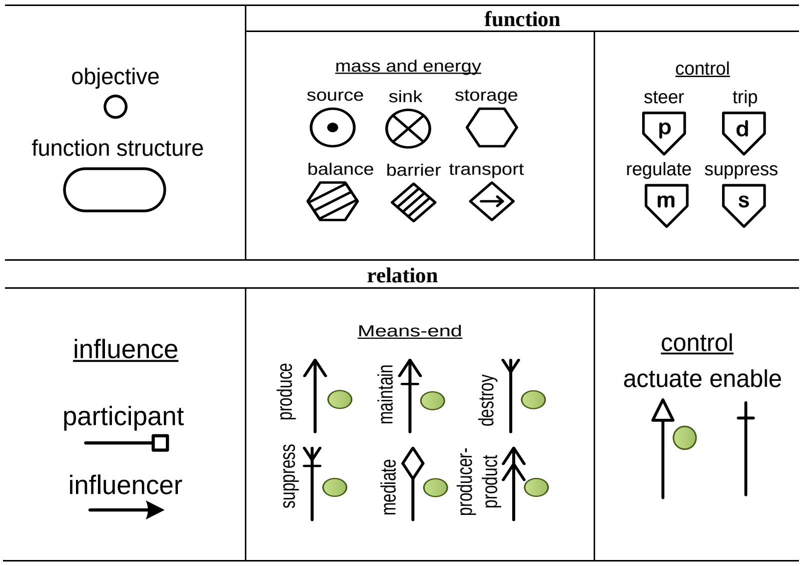

Fig. 1 Basic MFM elements.

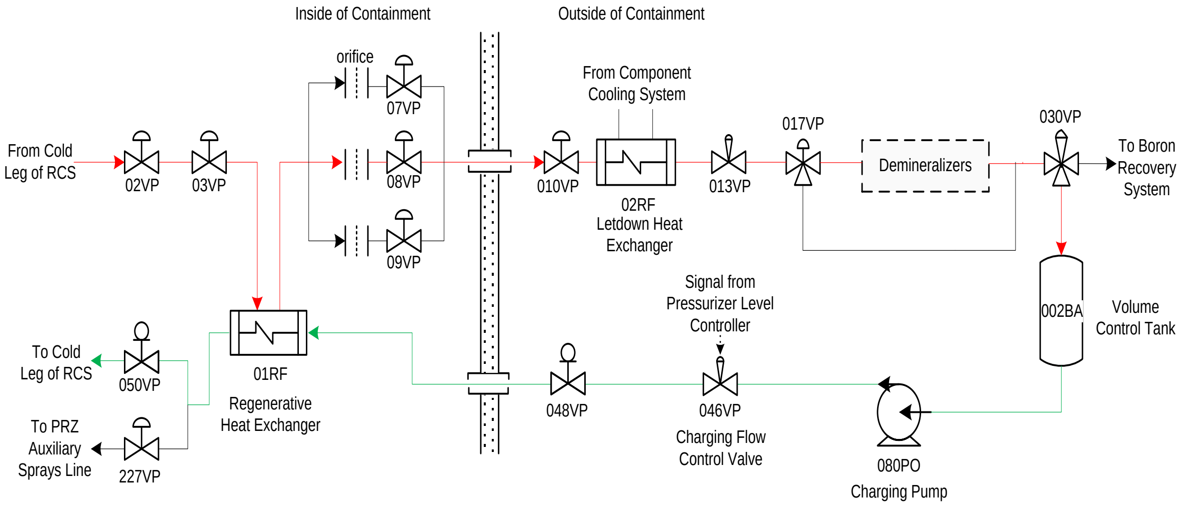

Fig. 2 Main flow paths of CVCS.

In most of the applications of MFM, the systems are assumed to be operated in a specific steady state. In practice, there is no doubt that the goals and functions of a system will change with the plant situation and task changes. On this issue, Lind *et al.* proposed a method to define the operational modes and demonstrated the method by modeling Japanese FBR plant Monju [15] and situation transitions of a LOCA accident in PWR [4].

This paper presents an application of MFM in modeling a process of operators taking operating procedures to recover the functions of a system step-by-step. On the one hand, operators naturally recognize all steps of the procedures from a functional and objective point of view as MFM can provide. On the other hand, different levels of abstractions in MFM may help operators identify the plant situation quickly and effectively without the overload of operators in information processing.

In the following sections, a brief introduction of CVCS (Chemical and Volume Control System) and its corresponding procedures will be firstly introduced. Then we will show how MFM can be used to represent four tasks during the performance of the procedures of the CVCS. Finally, we will explore the potential applications, such as emergency operating procedures management based on the proposed technology in this paper.

2 CVCS

CVCS is a major support system of the reactor coolant system (RCS) with the following major functions [16]:

(1) Maintain a proper inventory in RCS by maintaining the level of the pressurizer at the desired setting values.

(2) Purify the reactor coolant using demineralizers.

(3) Provide seal water for reactor coolant pump shaft seals.

(4) Provide auxiliary spray for the pressurizer.

(5) Provide borated water for emergency core cooling in conjunction with the High-head Safety Injection System (HHSI).

(6) Reactivity control in conjunction with Boron and Water Makeup System and Boron Recovery System.

However in this paper, we will only focus on the first two functions which are related to letdown and charging pipelines of CVCS to make the problem simplified.

2.1 Structure of CVCS

As shown in Fig.2, CVCS can be divided into letdown path (red line) and charging path (green line) by taking the volume control tank (002BA) as the boundary between the both. The reactor coolant is tapped off from the intermediate section of the cold leg piping of RCS through two series letdown isolation valves (02VP, 03VP). A regenerative heat exchanger (01RF) provides the initial cooling of the coolant by preheating the returning charging flow. From 01RF, the letdown fluid passes through one or more pressure reduction valves (07VP, 08VP or 09VP) where the pressure of the fluid is reduced by controlling the amount of reactor coolant that is removed from the RCS. Then, the fluid flows out of the containment to the letdown heat exchanger (02RF) via a containment isolation valve (010VP) for the final cooling. From the letdown heat exchanger (02RF) the fluid is delivered to the letdown pressure control valve (013VP) which automatically maintains a constant pressure of letdown piping. The cooled and depressurized letdown fluid is then directed to mixed-bed demineralizers which are designed to purify the coolant tapped off from RCS. The demineralizers are temperature sensitive, therefore a temperature diverting valve (017VP) bypasses flow around the demineralizers if the 02RF outlet temperature rises to the predefined limit (57℃). The purified letdown fluid then flows to the volume control tank (002BA) through a three-way valve (030VP) which will divert the letdown fluid to the boron recovery system in case of a high level in 002BA. The 002BA collects the letdown fluid, and provides a suction reservoir and head for the charging pump (080PO). A flow control valve (046VP) is used to regulate the charging flow rate. Downstream of the charging header isolation valve (048VP) is the tube side of 01RF where the charging fluid is preheated by the letdown fluid in the shell side of 01RF. The preheated charging fluid is directed to (050VP) cold leg of the RCS, or to (227VP) the pressurizer auxiliary sprays line.

2.2 Procedure task analysis

In this work, the task analysis for a block of EOPs [17] related to CVCS is performed firstly. The sequence of human actions is shown in Fig.3 after the appearance of two types of alarms of CVCS. Assume that the reactor is working in a steady-state power operation condition. When alarms related to the charging path or letdown path occur, operators need to perform required actions, *i.e.* Alarm signal cards in the figure, and the system will be isolated automatically or manually. In such cases, if it is possible to repair the system at power operation or hot shutdown conditions, the operators need to diagnosis and remove the failures, and then perform the procedure EOP-3.1 to restore CVCS to normal operation. Otherwise, operators need to boronize the coolant, *i.e.*, to increase boric acid content in the coolant before the temperature decreases below the cold shutdown condition by procedure EOP-3.2.

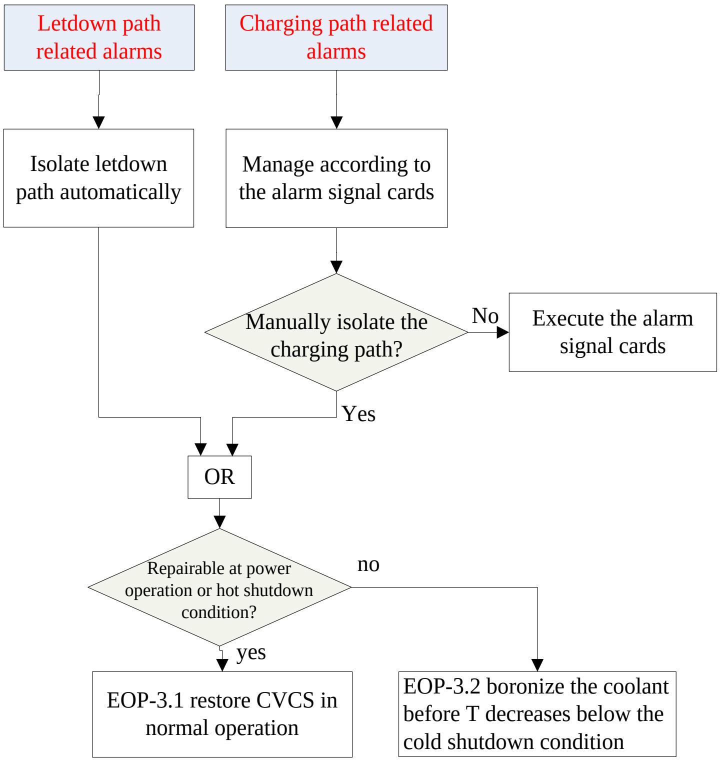

Fig. 3 The sequence of actions after alarms of CVCS.

Table 1 Task lists of EOP-3.1

EOP	Operation tasks	subtasks/actions		Components
3.1	3.1.1 Establish flow of charging path	Put the 046VP controller in manual mode, and close it to 0%		046VP
		Put the pressurizer level controller at 0% in manual mode		
		Open charging isolation valve 048VP		048VP
		Open charging isolation valve 050VP		050VP
		Put 046VP controller in automatic mode to establish approximately 6m^3/h of charging flow, and keep the flow rate 10minutes		046VP
	3.1.2 Enable functions of letdown pipelines	(1) Enable functions of the regenerative heat exchanger (01RF)	verify letdown pressure control valve 013VP in automatic mode, and ensure the setting values of 013VP at 20~25bar	013VP
			Open containment isolation valve 010VP	010VP
			Open letdown isolation valve 02VP	02VP
			Open letdown isolation valve 03VP	03VP
		(2) Establish flow of letdown path	Put the 046VP controller in manual mode, and adjust flow to 10m^3/h.	046VP
			Open one of orifice isolation valves	07VP/ 08VP/ 09VP
	3.1.3 Restore the normal operation	Put the pressurizer level controller in automatic mode		
		Adjust the 046VP controller in manual mode to put the level of pressurizer at setting values		046VP
		Put the 046VP controller in automatic mode		046VP

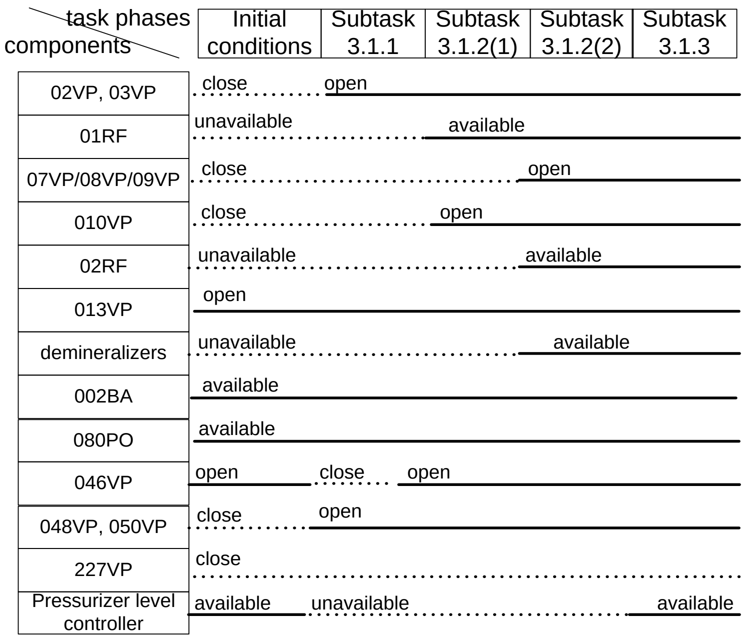

Fig. 4 transitions of the state of each component during the performance of the EOPs.

A set of tasks is needed to execute to complete the EOP- 3.1, the detailed tasks for which are shown in Table 1. For restoring CVCS to normal operation, operators need to perform three tasks, to establish flow of letdown path (Task 3.1.1), to enable functions of letdown pipelines (Task 3.1.2) and to restore the normal operation (Task 3.1.3). In task 3.1.1, setting the charging flow control valve and the pressurizer level controller at 0% in manual mode are necessary actions for performing the flowing steps. Then operators should open two isolation valves in order. Finally, a normal charging flow rate is established. In the process of enabling functions of letdown pipelines, a subtask of restoring the functions of regenerative heat exchanger must be firstly implemented by opening several isolation valves. Then the letdown flow can be established by opening one of orifice isolation valves.

The sequence of steps and corresponding components for executing each task are also listed in Table 1. Figure 4 shows the transitions of tasks and the state of each component in each task.

3 Modeling procedural tasks

MFM has been developed so that it can represent goals and functions of complex process plants. A procedure consists of a sequence of steps to accomplish tasks. Each task has its own specific goals to be achieved by components, structures, systems or operators. During the tasks of preparing, conducting and completing a procedure, the goals of individual tasks may change by the following ways in accordance with the different states [18] .

1) Immediate achievement: This means that the goal should be achieved at the present time because the criteria for goal achievement such as a specific flow rate are met. It does not necessarily mean that the goal will retain the achieved state in the near future.

2) Future achievement: The goal will remain or will be achieved (as in immediate achievement) in the foreseeable future. This aspect of achievement is of interest to the agent (human or automation) that manages the flow functions in the structure. A human operator or automation should influence the flow functions in such a way that the goal will remain achieved in the foreseeable future. In this study, future achievement means that goals, such as to maintain a constant of the pressurizer level can be achieved later if operators follow the remaining steps of EOPs.

3) Soundness of achievement: When achievement for a goal is sound, there is proper support for achieving and maintaining that goal. This means the

functions needed to achieve the goal do exist or have been enabled, and they make the achievement of the goal stable.

Those three states of goals achievement are distinguished by different symbols in the MFM model, as shown in Fig. 5.

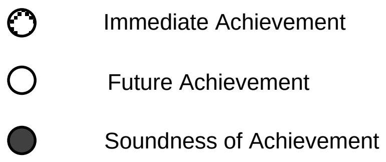

Fig. 5 Symbols for states of goals achievement.

By considering the three states of system goals, it becomes easy for operators to aware the current task phase and system situation because they perform procedures from the perspective of achieving the specific system goal. Immediate achievement means this goal needs to be achieved in current task, and future achievement means this goal is going to be achieved in the future task. When the achievement of a goal is treated as a condition of the current task or has been achieved in the previous tasks, the state of this goal is soundness.

3.1 MFM model for initial condition

Figure 6 shows the MFM model for the initial condition of the selected procedures of CVCS. There are two interrelated mass flow structures in the model. Mfs1 represents that the coolant stores and flows in reactor coolant system. Two storage functions sto_RCS and sto_PRZ represent coolant storage in RCS and the storage of water and steam in the pressurizer, respectively. There is water interaction, *i.e.*, the bidirectional flow of water in the pressurizer surge line between these two storage functions through two transport functions. Assume that the RCS has two-loops. CVCS is designed to letdown coolant from the intermediate section of cold leg pipings of one loop (coldlegA) and charge coolant to the cold leg of another loop (coldlegB).

Mfs2 simply represents the water flow in CVCS. In the current state, both the letdown and charging pipelines are isolated due to the failures of CVCS. The isolation of pipelines is represented by two barrier functions. The purposes of the analyzed procedures (EOP-3.1) are to restore the charging and letdown pipelines in normal operation, *i.e.*, to change barrier functions to transport functions (tra_charging and tra_letdown). After performing EOP-3.1, two objectives of CVCS, *i.e.*, to maintain level of pressurizer and to purify the coolant are achieved. Note that the state of these two objectives are future achievement. The other functions of CVCS such as providing reactor pumps shaft seals are not considered in detail in this study.

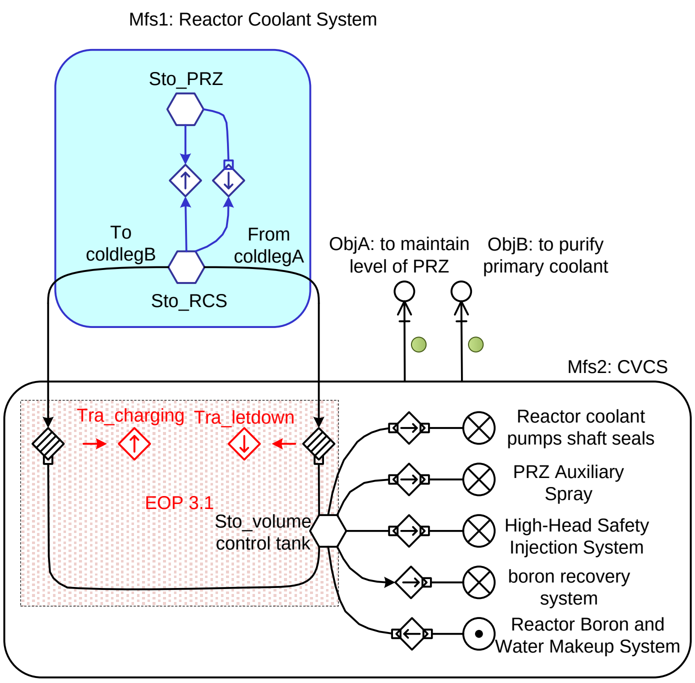

Fig.6 MFM model for the initial condition.

3.2 MFM model for task 3.1.1

After operators perform the task 3.1.1, functions of charging pipelines are enabled and a required charging flow rate is established. The MFM model for this subtask is shown in Fig. 7. Wherein, Efs1 represents the energy conversion process in the charging pump (080PO), Sou1 represents the power supply, and tra1 and sin1 represent conversion of the electricity into kinetic energy in the water.

In Fig. 7, Mfs1 represents the functions of water flow in CVCS, Tra2 represents the transportation of water resulting from the energy conversion represented by efs1, and they are connected by a produce-product relation (pp1). Sou2 represents water source in 002BA which provides water supply for the charging pipelines. Tra3, tra4 and tra5 represent the water transportation in 046VP, 048VP and 050VP, respectively. The water is charged back to coldlegB represented by the sink function sin2. Obj1, *i.e.*, a required charging flow is immediately achieved in current state, and this objective can enable the transport function tra_charging. However, since the letdown pipelines are isolated, only if the remaining procedures are performed successfully obj2 which represents a normal letdown flow can be achieved.

3.3 MFM model for subtask 3.1.2 (1)

The MFM model for subtask 3.1.2 (1) is shown in Fig. 8, where functions of the regenerative heat exchanger 01RF are enabled after operators open 03VP. In the current situation, the coolant can be tapped off from coldlegA (sou3) through 02VP (tra6) and 03VP (tra7) to the shell side (sto1) of 01RF. Bra2 and sin3 represent the isolation of material flows in the downstream of 01RF. The barrier function bra1 prevents water interaction between two sides of the heat exchanger. Since operators have already restored the charging pipelines, some functions are no need to be focused on. The function flow simplification [19] to change the aggregation level of an MFM model is implemented in the charging pipelines. Tra2* represents an equivalent transport function of the complicated flow from sou2 to bal3. Note that the state of the achievement of obj1 in current state turns to be soundness.

Energy flow structure efs2 describes heat transfer functions in the water flow of CVCS. Energy in coldlegA (sou4) is transported (tra8) to the shell side of 01RF (sto2), then the energy preheats (tra9) the water transported (tra10) from 002BA (sou5) to the tube side of 01RF (bal5). The outlet of 01RF is transported (tra11) to coldlegB (sin4). The heat cannot be transported downstream of 01RF in the letdown pipelines because of existence of a barrier function (bar3). Since the transportation of energy represented by tra8, tra10 and tra11 are mediated by the flow in the water flow, they are connected with tra7, tra2* and tra5 in mfs1 by mediation relations (me1, me2 and me3). Obj2a, *i.e.*, the normal heat exchange function of 01RF is immediately achieved after executing this subtask.

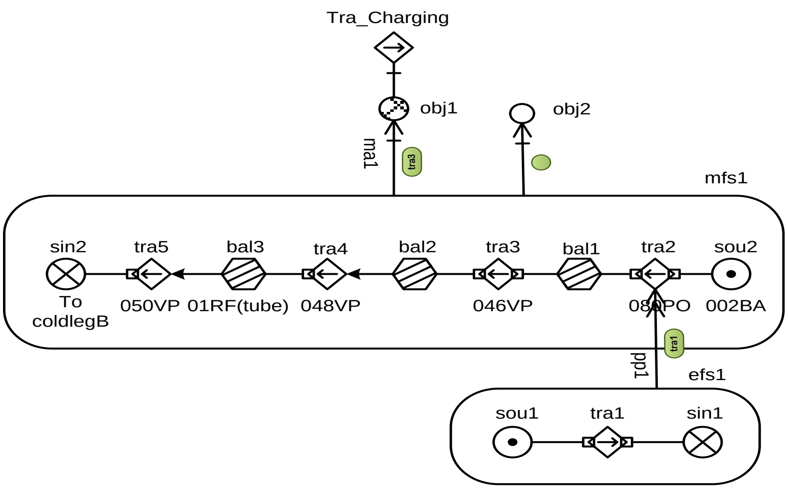

Fig. 7 MFM model for subtask 3.1.1.

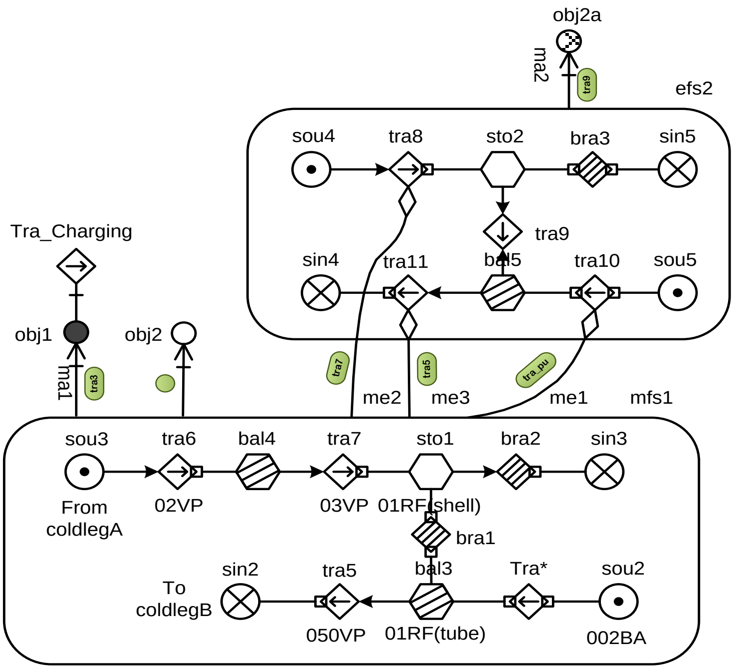

Fig.8 MFM model for subtask 3.1.2 (1).

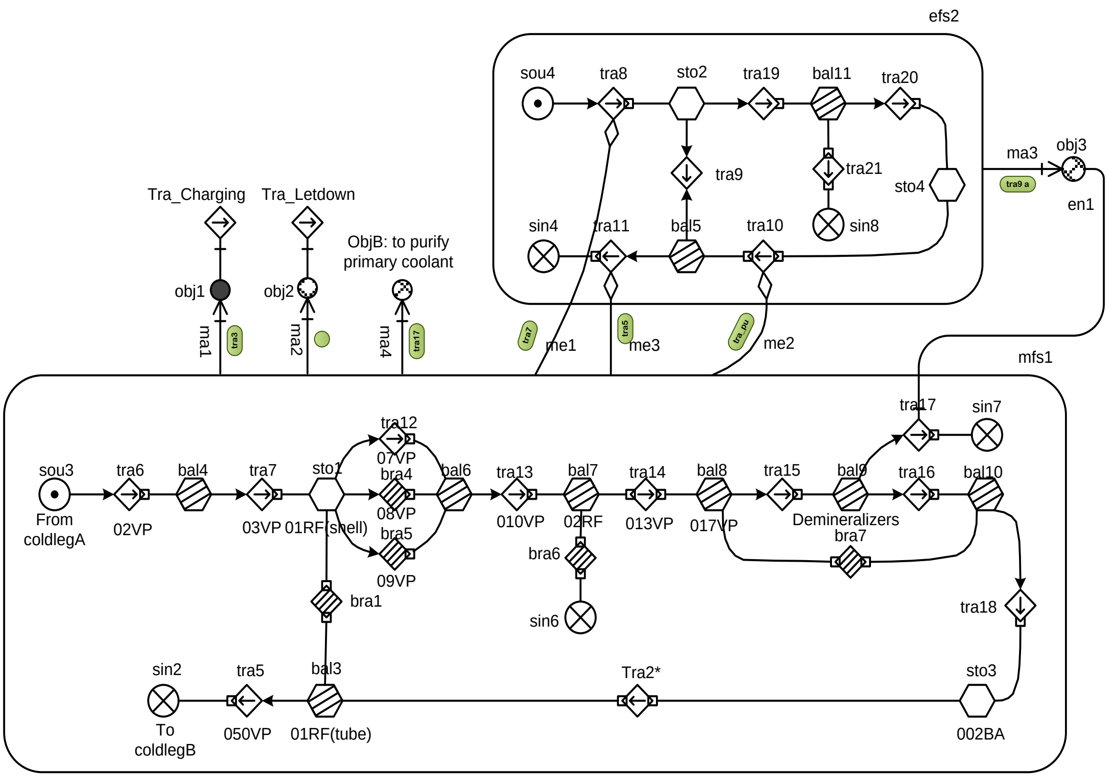

Fig.9 MFM model for subtask 3.1.2 (2).

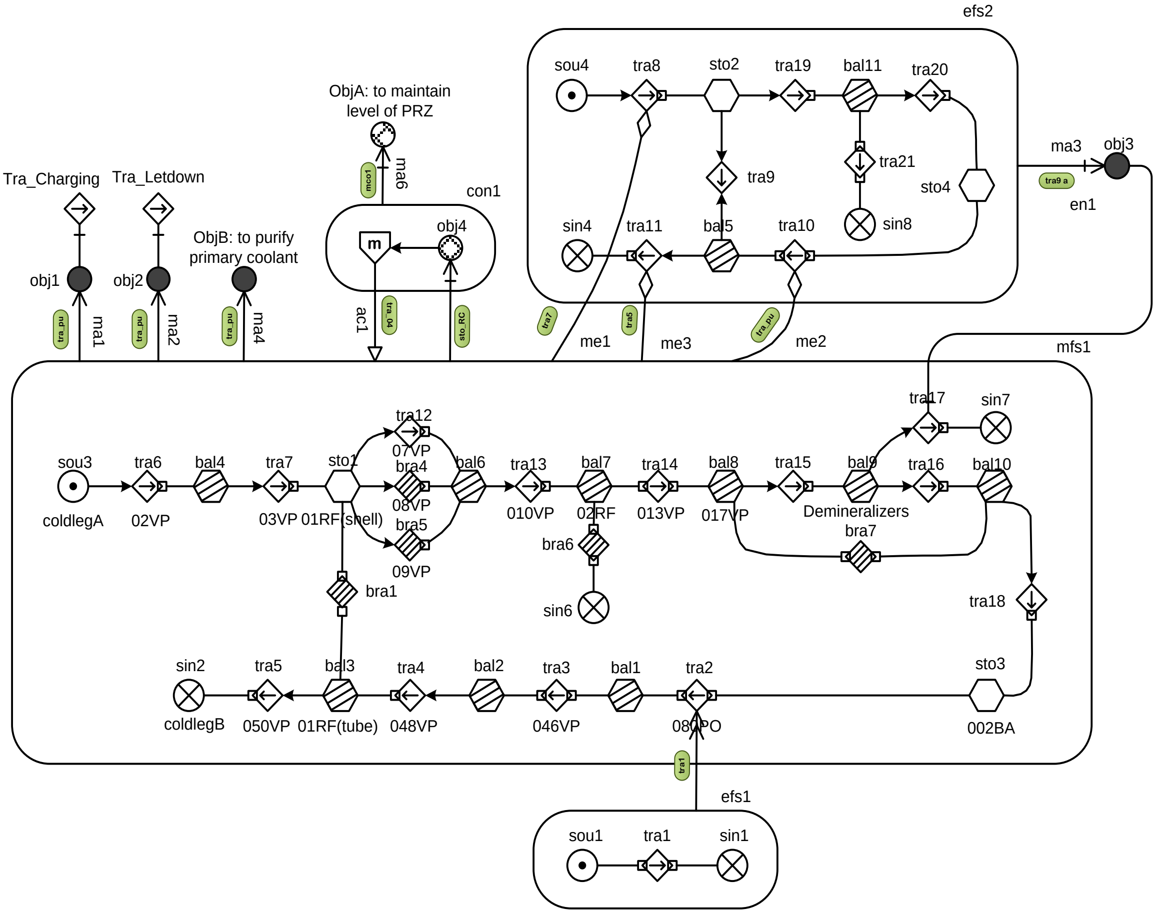

Fig. 10 MFM model to restore CVCS to normal operation.

Table 2 Change of states of objectives by the performance of EOP-3.1

Objectives	Description	State after Task3.1.1	State after Task3.1.2(1)	State after Task3.1.2(2)	State after Task3.1.3
ObjA	To maintain level of PRZ	Future achievement	Future achievement	Future achievement	Immediate achievement
ObjB	To purify primary coolant	Future achievement	Future achievement	Immediate achievement	Soundness of achievement
Obj1	A required charging flow	Immediate achievement	Soundness of achievement	Soundness of achievement	Soundness of achievement
Obj2	A normal letdown flow	Future achievement	Future achievement	Immediate achievement	Soundness of achievement
Obj2a	The normal heat exchange function	Future achievement	Immediate achievement	Soundness of achievement	Soundness of achievement
Obj3	A required temperature for the letdown flow	Future achievement	Future achievement	Immediate achievement	Soundness of achievement

3.4 MFM model for subtask 3.1.2 (2)

The other part of the letdown pipelines will be restored after operators perform the subtask 3.1.2 (2). The enabled functions are shown in the MFM model in Fig. 9. In mfs1, the water in sto1 is transported to the demineralizers through 07VP (tra12), 010VP (tra13), the letdown heat exchanger 02RF (bal7) and 013VP (tra 14). The bypass of the demineralizers from 017VP (bal8) is isolated by bar7. Tra16 and tra17 represent the water transportation and the impurities removal, respectively. The letdown fluid finally flows (tra18) to 002BA (sto3). At this point, the objective obj2 to enable the transport function of the letdown pipelines is immediately achieved. Simultaneously, one of CVCS functions restored during performance of EOP 3.1, *i.e.*, purifying the primary coolant (objB) is immediately achieved via tra17 which represents the impurities removal in the demineralizers.

In efs2, the heat transfer from 01RF (sto2) to 002BA (sto4) is established in this phase. The energy transportation (tra9) in 01RF and heat removal (tra21) by the component cooling system in 02RF ensure the immediate achievement of obj3, *i.e.*, the temperature requirement of the letdown flow to enable the purifying function of the demineralizers. This support function is represented by an enable relation (en1) connecting obj3 with tra17.

In efs2, the heat transfer from 01RF (sto2) to 002BA (sto4) is established in this phase. The energy transportation (tra9) in 01RF and heat removal (tra21) by the component cooling system in 02RF ensure the immediate achievement of obj3, *i.e.*, the temperature requirement of the letdown flow to enable the purifying function of the demineralizers. This support function is represented by an enable relation (en1) connecting obj3 with tra17.

3.5 MFM model to restore CVCS to normal operation

The purpose of task 3.1.3 is to restore the pressurizer level controller which is stopped before. After performing the last task of EOP-3.1, CVCS is put into normal operation. The MFM model for normal operation is shown in Fig. 10. The functions of the pressurizer level controller are represented by cfs1 in the model. Another purpose of CVCS (ObjA), *i.e.*, to maintain the pressurizer level at its setting values is immediately achieved and it is therefore related to the water inventory in the sto2_PRZ. The actuation relation act1 connects the control function con1 with tra3 in mfs1 as indicated by its label, *i.e.*, the level of the pressurizer is kept constant by regulating the water transferred by the flow control valve 046VP. So far, the functions of letdown and charging pipelines are enabled and two functions of CVCS, *i.e.*, to maintain level of the pressurizer and to purify the coolant are both achieved. It means that the EOP-3.1 is performed successfully. Table 2 summarizes how the states of achievement all the objectives or sub-objectives involved in the analysis procedures of CVCS are changed as operators perform the procedures.

4 Discussions

It has been shown that the MFM can provide a formalized way to represent different tasks and system states as the performance of procedures as presented in the previous chapter 3. Since the flow functions and objectives in MFM models are not only logical concepts but also have a general representation of physical characteristics of the real system, the measurement of the physical characteristics can be obtained from solid data of simulators or actually NPP systems [20].

As an application, it is instructive to use the MFM models as constructed in this paper to combine with the operating data for the EOPs management. An example of a prototype EOP interface with MFM models is shown in Fig.11. When operators execute actions in EOPs, MFM model for the current task is displayed on the lower right of the interface, and the MFM model can simultaneously record the state transitions of every flow function and objective during the procedures. A table on the upper right of the display shows how the states of achievement of all the objectives involved in the procedures are changed during the process of executing different tasks. When a task is accomplished, the MFM model is updated for the next task. Due to the nature that the MFM models are task-specific and hierarchical, operators can follow the EOPs in different levels and with different foci in different task phases. It is expected that it can provide a strategy for supporting the performance of the procedures and improve situation awareness of operators when they will implement the operating procedures.

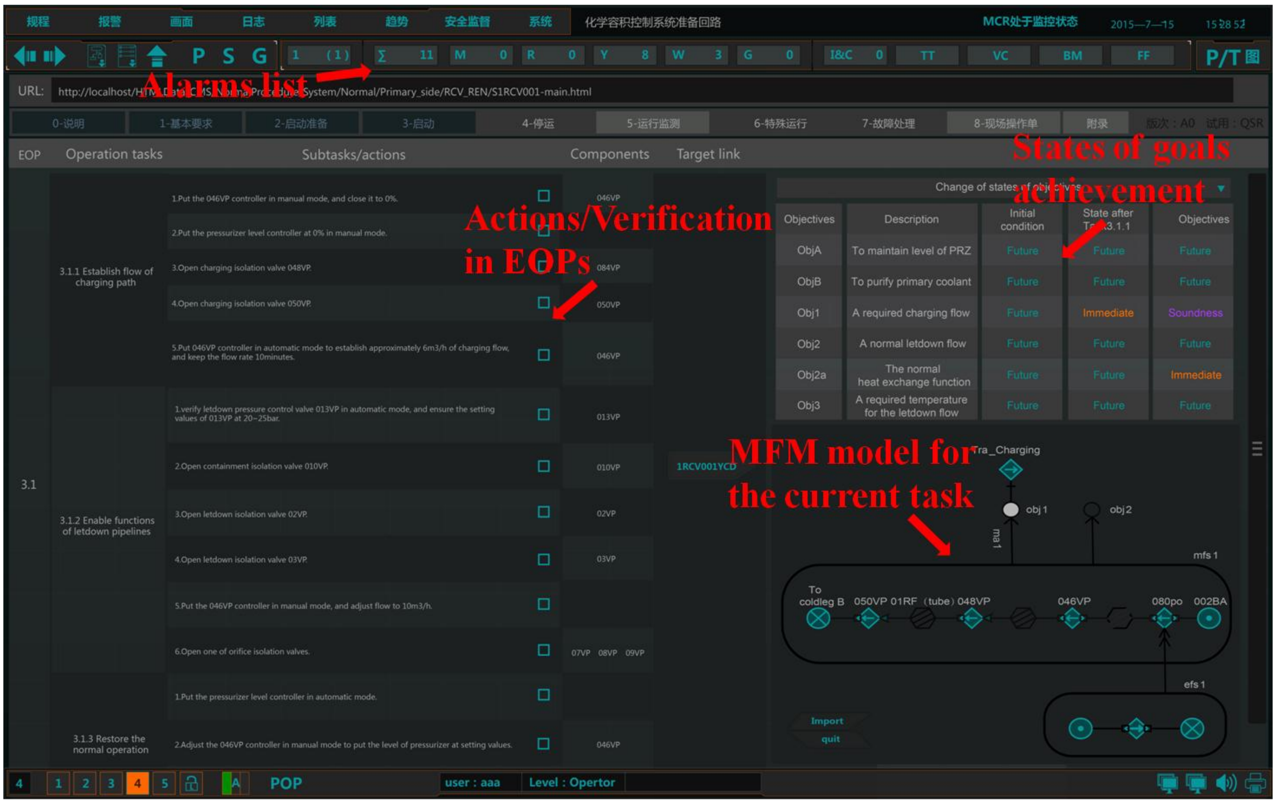

Fig. 11 Example of a prototype EOP interface with MFM models.

There are also several potential applications based on the given MFM models of operating procedure tasks. As was mentioned in the introduction of this paper, MFM is a powerful tool for cause-consequence reasoning to be used for diagnosis management of plant failures. In this respect, Gofuku [13] has developed a dynamic operation permission by predicting the influence of an inappropriate operation based on MFM reasoning theory. By utilizing the models presented in the paper, influence analysis of some human errors of commission can be performed during the performance of a procedure such as input error of flow rate of a control valve. Moreover, critical human errors can be further identified.

On the other hand, Yang, *et al.* [21] proposed a system reliability modeling and analysis method based on MFM. Inspired by this reliability analysis method and MFM models for procedure tasks in the present paper, the reliability of the achievement of specific system objectives can be further analyzed by giving appropriate failure data of various components. It is expected that this technology can be further used for system reliability monitoring.

5 Conclusions

The paper has shown how the concepts of Multilevel Flow Model (MFM) can be used to represent system functions and objectives of different operating procedure tasks. According to the available functions in the system and achieved task objectives in different duration in the process of performing procedures, each of MFM models representing a task phase or a specific system state is constructed and demonstrated. It is concluded that MFM can provide a formalized methodology of defining the procedure tasks and states transitions of systems during the performance of procedures.

Due to the nature that different viewpoints should be focused or integrated by operators in different phases of a procedure, it is expected that the proposed study can provide effective operation knowledge for operators and improve situation awareness of them, and further be used to successful management of emergency operating procedures.

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