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Modeling of Operator's Actions on a Nuclear Emergency Condition Using Multilevel Flow Modeling

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A B S T R A C T

In nulear emergency condition, after determining the initiating event and the type of the anomaly, operators should take counteractions to control the reactor to mitigate the accident and to bring back the plant to the safe condition. The actions should based on emergency operating procedures. In order to minimize the human error related to the actions, some necessary information is needed. Such kind of information is the consequence of the actions, which can be derived by modeling the counteractions. Multilevel flow modeling (MFM), a functional modeling, is chosen to model the counteraction with the consideration that it is based on cause-effect relations and consequence reasoning, it provides realization relationship which corresponds physical components with their functions, and it provides comprehensive diagnosis based on human perspective of the system objectives. The counteractions are represented by the control functions in the MFM. This paper discusses how to model the counteractions and the consequences of the actions to the system components, which are necessary to enhance situation awareness and to reduce human errors.

1. INTRODUCTION

Research and development of reactor safety and technology is one of the main focus of five year plan 2015-2019 of BATAN, especially for preparing the construction of the first nuclear power plant (NPP) in Indonesia. Some analysis and evaluations related to the technical aspects of the plant including core reactor, reactor safety systems, instrumentation and controls, and so on, have been undertaken. Besides the technical factors, human factor is one of important aspects of safety in nuclear power plants and should be considered fom designing process to operation phase of the plants.The benefits of considering human factor are the performance of the safety functions can be optimized as well as the improvement of the effectiveness of reactor operation [1, 2].

Human factors are correlated with the operators of nuclear power plants, which their main tasks are to monitor and to control the reactors. In normal operation, they should monitor the plant status through a large screen display and have to make sure that component paremeters are in normal level. However, when anomalies occur, indicated by the deviation of the parameter levels, they should determine the initiating event, cause of the anomalies, and then conduct some appropriate actions to control the reactor and bring back the plant to the safe condition. In a well known abnormal condition, the operator actions are related to the input signal validation, plant and system status identification, and also refer to the emergency operating procedures (EOPs).

In addition, the counteractions should be conducted appropriately to reduce human error.

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There are two types of human errors related to the counteractions: commission errors and omission errors. Commission errors are type of errors caused by operators misconduct, while omission errors happens when operators omit some steps of the counteractions.

The counteractions of operators in one case can recover the state of a controlled component and in other case will affect other components and the system. The consequences of the counteractions should be anticipated by operators to minimize the human errors and to keep the plant in safe condition.

Therefore, the information about the impact of the counteractions is needed by operators. It can be achieved by modeling the counteractions using multilevel flow modeling (MFM). The counteractions can be modeled by using control functions in MFM. The counteractions include the objective of the action, condition of actions and component to be controlled. It is relevant to the concept of control function in MFM.

The information of the impact of the counteractions can be gathered by implementing cause-effect relation and influence propagation in MFM. Controlling a component by changing its state will affect other components in the system. The state of the affected components should be monitored and considered. Therefore, the kind of information is necessary for operators to do the control task to mitigate the accident without any mistakes.In addition, it will increase the situation awareness of the operators. Situation awareness is the ability of operators to receive and understand the information of the plant status, and to predict the future state of the plant based on the information [3].

This paper discusses the modeling of operator actions in mitigating an emergency condition using MFM control functions. In the MFM model of PWR plant, a Steam Generator Tube Rupture (SGTR) accident scenario is applied as a case study. A simplified EOP of SGTR accident is used by operators to mitigate the accident. One of the procedure step, which is “Reactor Coolant System (RCS) cooldown using steam dump through steam dump valve”, is discussed. The purposes and benefits of the modeling (the purpose and impact of the control actions) are investigated by implementing the cause-effect relations and influence propagation rules in MFM.

2. OPERATOR’S TASKS

During the operation of nuclear power plants, anomalies may happen indicated by the change of parameter level of some important components related to safety. In addition, it is also indicated that the states of components are changed, for example, from normal to abnormal value, from high to low value or vice versa.

The anomalies, in the worst case condition, can cause the plat operated in abnormal and emergency condition. In addition, it will impact the intergrity of the reactor core and public because of the realeasing of radioactive material to the environment.

Therefore, control actions are needed to change the state of components and to bring the plant back to the normal and safe operation. The purpose of control systems is to make sure that material and energy balance are managed, which in turn to keep the safe operation of the plant [4]. In addition, operators should have appropriate information about the purpose and function of the control system, especially in case of diagnosis and counteractions of the anomalies in the plant [4]. This information is necessary to determine the cause of the disturbance of the plant and the impacts of the counteractions. However, the information of the purpose of the control system usually is not provided from P&I diagram but from knowledge of the expert about the design problem [4].

Related to the mitigation of emergency conditions, operators should refer to the EOPs. Since the anomalies have been identified as well as the initiating event and the type of the accident, they should select the appropriate EOPs and follow the procedure steps completely. Moreover, they should make sure that there are no mistakes and errors while conducting the counteractions. The next section discusses the overview of the EOP.

3. EMERGENCY OPERATING PROCEDURES

Operation procedures provide information and guidance for operators to operate and monitor the plant during normal operation; and help them to make decision and to take counteractions during an emergency condition in order to mitigate the accident, and to bring the plant into safe operation condition as in **Fig. 1**. The information and guidance are combined to minimize human error.

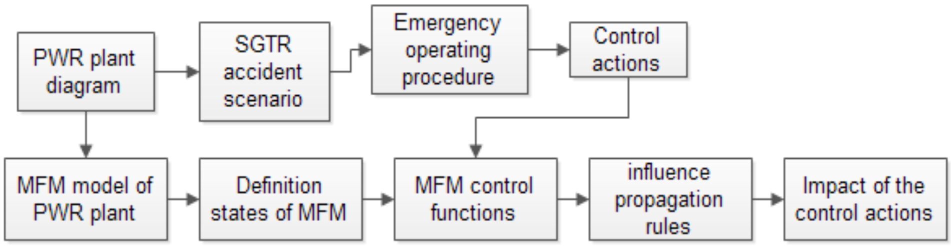


Fig. 1. Modeling the counteractions

During the life time of the plant, some anomalies may happen in the plant. Based on the anomalies, the plant conditions can be divided into three conditions: abnormal conditions, accident/emergency conditions, and severe accident conditions depending on the severity of the anomaly. In abnormal conditions, the anomalies do not cause any significant damages to safety related components and can be handled by normal control systems. The anomalies are indicated by the alarm messages and changing the parameter level of components from the normal setpoints. In this case, operators should implement an appropriate alarm response procedure to identify the anomalies. In some cases, the abnormal operation may change to a more complex operation condition if the malfunctions happened in core cooling system or in a support system. Operators should do the counter actions to compensate the malfunctions or faults following the abnormal operating procedures (AOPs). Examples of abnormal conditions are malfunction of a component of normal running plant and a fault in the function of a component of control system.

Examples of accident conditions are steam generator tube rupture (SGTR), loss of coolant accident (LOCA) and loss of offsite power (LOOP). In case of emergency, the used procedure is emergency operating procedure (EOP). Operators should follow the EOP to control the plant and cannot only rely on their knowledge and experiences.

When the accident conditions reach the severe condition, severe accident guidelines (SAGs) is used to mitigate the accident. Severe accident conditions are accidents which include significant core degradation. SAGs are used when the EOPs cannot effectively preventing the core damage. Compared with EOPs which focus on preventing core damage, SAGs concentrate on maintaining other barriers for protecting the release of radioactive materials to public.

4. METHODOLOGY

The paper discusses the modeling of operator actions by apllied the control function in MFM as can be seen in **Fig. 1** The overview of MFM including the MFM control function which is useful for modeling the operator actions will be discussed. An example is given to describe the modeling of the operator actions and their impacts to other components and the system.

4.1. Overview of MFM

Multilevel flow modeling (MFM) was developed by Morten Lind [5] to model the complex industrial plants in term of functions and objectives and their interconnected relations, In other words, it represents systems in means (functions) to achieve ends (objectives) relations.

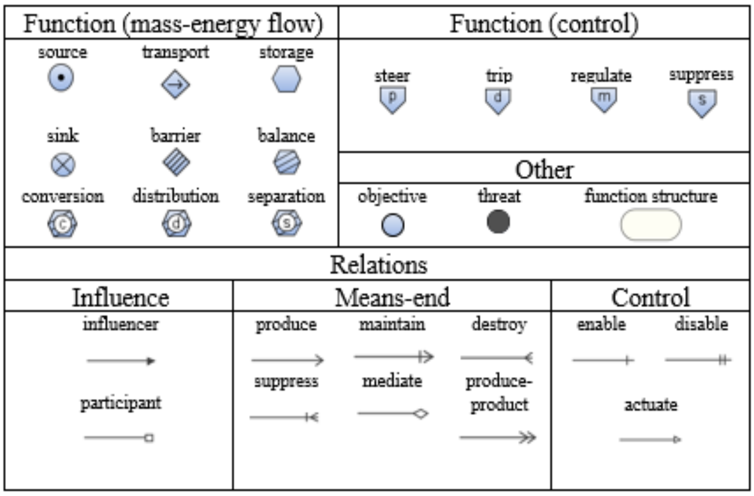


Fig. 2. MFM symbols

MFM has been widely used for alarm and root cause analysis [5], counteraction and dynamic operation permission [6, 7], supervisory control [8], and faults diagnosis [9] in nuclear, chemical and electrical power engineering.The functions and objectives in MFM are represented by symbols as can be seen in **Fig. 2**, which consist of functions (such as source, transport and storage) and relations (influence, means-end and control). The functions correlate with the physical components of plant, for example, a transport function is correlated with a pipe and a tank is represented by a storage function. An MFM model generally consists of mass flow systems, energy flow systems, control systems and objectives. Each of function primitive is connected by influence relations.

4.2. Overview of MFM control functions

Operator's action or a counteraction conducted by human is a manual intervention to the system. The purpose of the counteractions is to change the state or produce a new state of a component or a system by controlling or changing the state of other component based on the operational or control condition values. In case of nuclear power plant, the objective is to change the plant state in a safer one and/or to mitigate the influence of an anomaly.

A simple example of counteraction is controlling water level of a tank as seen in **Fig. 3**. The idea is that a tank is filled by water through a pump and a valve. When the water reach the minimum level, the valve is opened and the water flows from the pump to the tank. The valve will be closed if the water reaches the maximum level in the tank which will stop the flow water to the tank. Based on the example, the purpose of the control action is to fill the tank with water in a predefined value, the operational condition is the water level, the controller is human or automatic system to open or close the valve; and the component to be controlled is the valve.

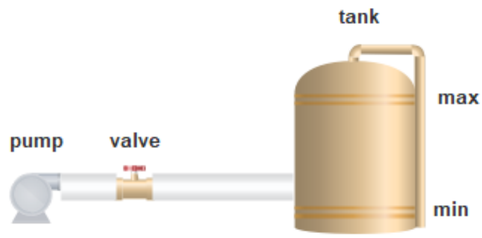
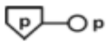
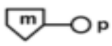
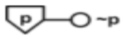
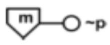


Fig. 3. Simple water tank diagram

MFM as a functional modeling of complex industrial plants also accommodates the control functions, represented by the control functions in the MFM symbols (**Fig. 2**). The concept of control function in MFM was proposed by Lind [10] and has been implemented in some studies [11,12]. Lind in [10] describes that there are several types of control functions in MFM (steering, regulation, tripping and interlock) as can be seen in **Table 1**. From the table, the steering function ensures that p is produced or in other words, it is used to produce a new state of a component or a system. It is relevant with the counteraction which is to produce of a new state of a function. Therefore, the counter action is modeled using MFM control function, based on the idea proposed in [10], as can be seen in **Fig. 4**. Control structure (cfs1) represents the counteraction/operator action from which to produce a new state of a storage function sto1 (a function to accumulate mass or energy) in mass flow system mfs1 (represents a system to deliver mass or material) as the conditional operation or system objective. Then the conditional operation will actuate the production control function pco1 (which is used to produce a new state), which represents the operator, to change the state of the transport function tra1 (a function to transfer mass or energy) to accommodate the new state of sto1. In case of water tank (**Fig. 3**), the operator who controls the valve is represented by pco1, a component to be controlled (tra1) is the valve, and the objective obj1 (represents a state which should be produced) of the system is to fill in the tank (sto1) with water.

Table 1. Type of control functions[10]

Task	Symbol	Purpose
Steering		Ensure that p is produced
Regulation		Ensure that p is maintained
Tripping		Ensure that ~p is produced
Interlock		Ensure that ~p is maintained

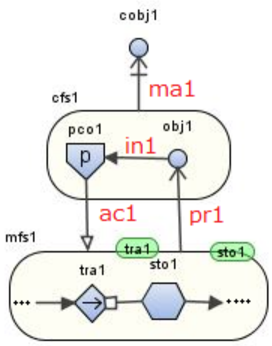


Fig.4. MFM control functions[13]

4.3. MFM Model of PWR Plant

In this study, a simplified diagram of pressurized water reactor (PWR) plant is used, as can be seen in **Fig. 5** [13]. A PWR system has primary system and secondary system. Primary system transfers heat generated in the fuel and stored in reactor vessel to the steam generator. The steam generator produces steam and then the steam is introduced to turbine to rotate the electric generator. The mechanical energy to rotate is in turn converted to electricity (electrical energy). The steam that some heat energy is lost will be delivered to the condenser and condensed into water and then transferred to the steam generator.

A PWR also has safety systems which will be functioned in case of emergency. When an anomaly happens in the plant,for example loss of coolant accident (LOCA), the reactor will be automatically shutted down by the reactor trip and then the safety injection signal is actuated to operate the emergency core cooling system (ECCS) to provide water to the reactor coolant system. Although the reactor is shutdown, it still produces decay heat. The decay heat should be removed to cooldown the reactor by bypassing the turbine and dumping the steam to the condenser. The cooldown process then is completed by the residual heat removal system.

The simplified PWR diagram is converted to the MFM model as seen in Fig.6. This model is a modification of the MFM model developed by [14]. The MFM model includes major PWR systems (primary system by mass flow structure mfs1 and secondary system by mfs2) and safety systems such as emergency core cooling system (efs9), residual heat removal system (sto1) and internal spray system (sto2). The further explanation of the MFM model of the PWR plant is provided in [13].

The main objective (obj1) of the MFM model of the PWR system is to generate the electricity. It can be accomplished by converting the heat energy into electrical energy. Initially the heat is generated in fuel (sou3 in efs1) installed in reactor vessel (sto3 in mfs1) and by fission reaction (represented by the energy flow structure efs1).

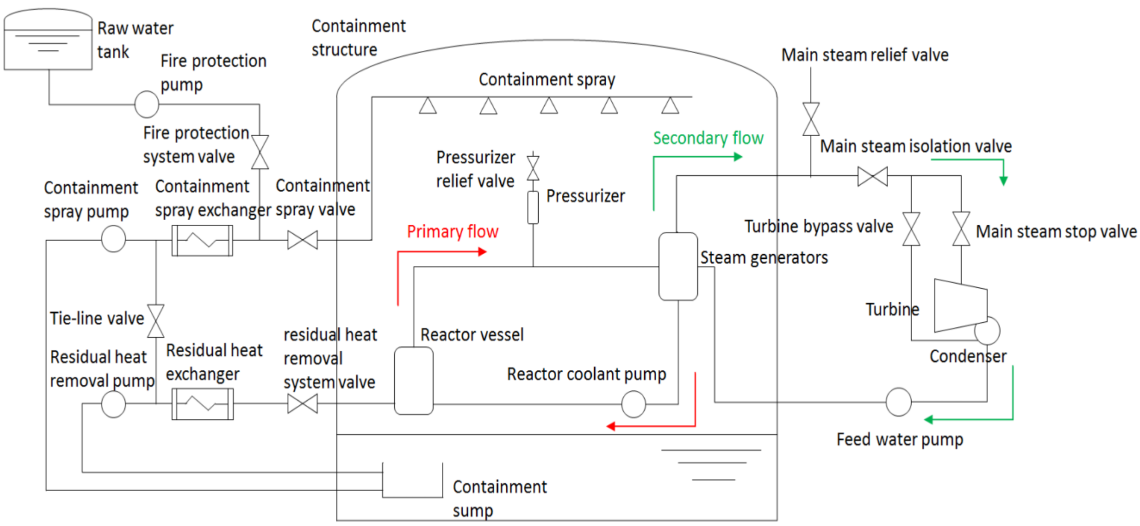


Fig. 5. Simplfied diagram of PWR plant[14]

The heat is transferred from primary system to secondary structure (efs7) through the steam generator bal14 (primary side) and sin3 (secondary side). Furthermore, the heat is converted into mechanical energy in efs6 to rotate the turbine and generator (efs8). Finally, the electrical energy is produced (obj1).

5. RESULTS AND DISCUSSION

5.1. Case study

As a case study for modeling the operator actions, a SGTR scenario is applied to the simplified diagram of PWR plant. Operators should do the counteractions to mitigate the accident refer to the EOP of SGTR accident, in this study, the simplified of EOP of SGTR accident of Mihama unit 2 [13]. However, only one procedure step will be discussed in this paper to describe the modeling of operator action.

SGTR is one of common and potential accident in PWR plants and there are some operator actions depending on the plant conditions.The SGTR accident is indicated by the decreasing of pressurizer level and pressure, increasing the level of steam generator, and increasing radiation in main steam line. The ruptured steam generator (SG) should be identified and isolated to prevent the release of radioactive material to the environment. In addition, the decay heat should be removed to cooldown the reactor.

The mitigation of the SGTR accident should refer to the EOP of SGTR accident and should be conducted step by step by the operators. For analysis purposes, this paper only discuss one procedure step of the EOP, which is: "RCS cooldown using steam dump through steam dump valve". **Figure 7** shows the part of MFM model of RCS cooldown using steam dump valve operation.This step is executed after the level of faulted/intact SG has been regulated to the setpoint value and the safety injection (SI) has been stopped.

After the reactor trip and safety injection operation, the reactor is in hot shutdown condition. It means that the residual heat remains in the system and should be removed by dumping the steam from the SG in order to cooldown the RCS. In case of the condenser is available, the steam can be dumped by bypassing the turbine and opening the steam dump valve to let the steam directly flow to the condenser.

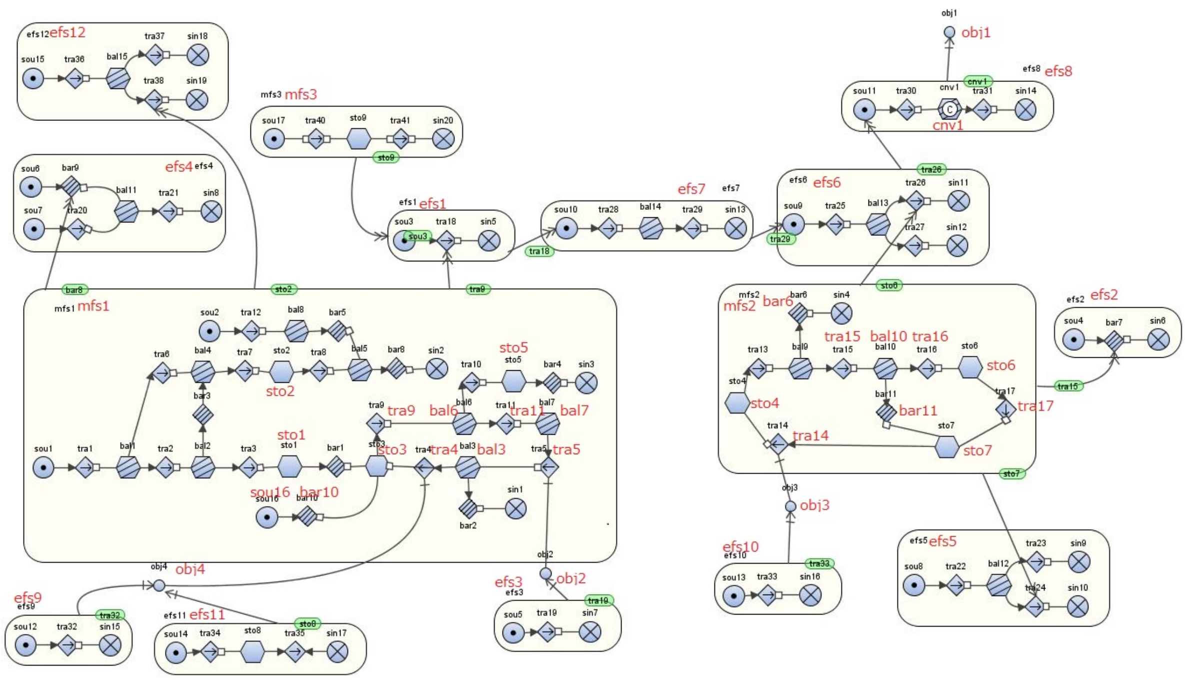


Fig. 6. MFM model of PWR plant [13]

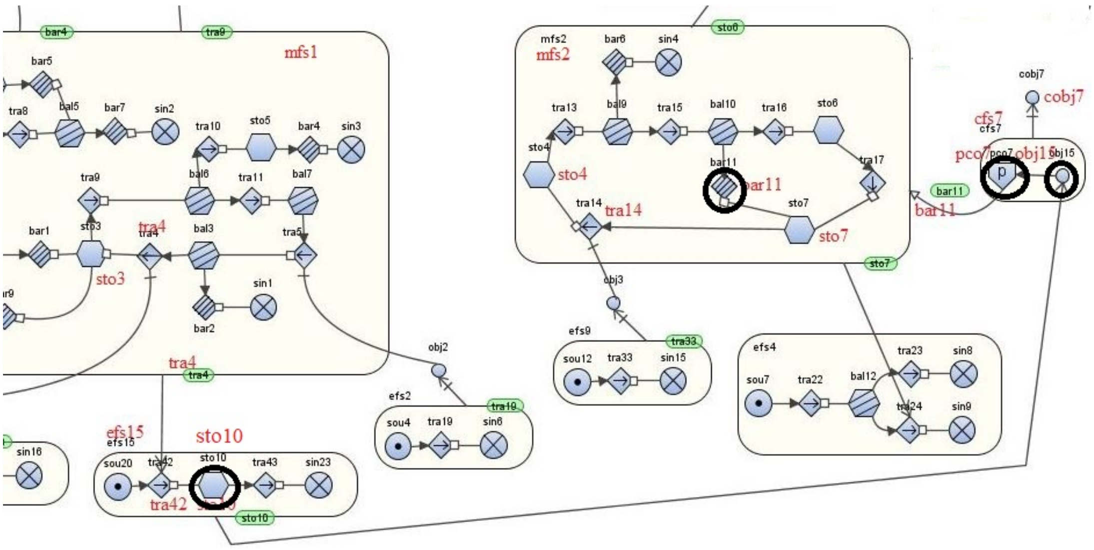


Fig. 7. Part of MFM model of RCS cooldown using steam dump valve operation

Table 2. Parameters of modeling of RCS cooldown operation

RCS cooldown using steam dump valve		
Items	Physical components	MFM model
Operation condition	Low temperature of RCS	Low volume of sto10 in efs15
Objective	To decrease the temperature of RCS	obj15
Control function	Open the steam dump valve	pco7: disable the bar11
Controlled component	Steam dump valve	bar11
Control objective	To open the steam dump valve	cobj7

In **Fig. 7**, the temperature level of the RCS is represented by the state of sto10 in efs15 (energy flow of RCS). Therefore, the operation condition is the low volume of sto10 which is correlated with the obj15, which in turn the control function pco7 (represent the operator action) is actuated to disable the barrier function bar11 (steam dump valve) in mfs2 (secondary function). If the barrier function is disabled, it means that the mass or energy can be transferred through the function. Therefore, it can be considered that the barrier function acts as a transport function (the valve is open).

The parameters of modeling the RCS cooldown using steam dump valve are provided in **Table 2**. As mentioned in the previous sections that the purpose of modeling the operator action is to derive the objective of the control action and to derive the impact of the counteractions. Therefore, to qualitatively analyze the impact of the counter actions, the influence propagation rules is implemented. In order to analyze the influence propagation, some definition of states of MFM are needed. The definition of states is based on [15] and modified by the author in [13] as can be seen in **Table 3**.

Table 3. Definition states of MFM [13]

Symbols	**States**
source	normal, high output flow potential, low output flow potential, <u>no output flow potential</u>
sink	normal, high input flow, low input flow, <u>no input flow</u>
transport	normal, high flow, low flow, <u>no flow</u>
storage	normal, high volume, low volume, <u>no volume</u>
barrier	normal, leak
balance	Normal (balance), unbalance (fill or leak)
threat	exist (high), exist (low), non-exist
Objective	true (high), true (low), false

Since the barrier function bar12 is disabled, it means that steam dump valve is open and it will let the large amount of steam directly flowing to the condenser (sto7: high). The states of components after the counter action are given in **Fig. 8**.

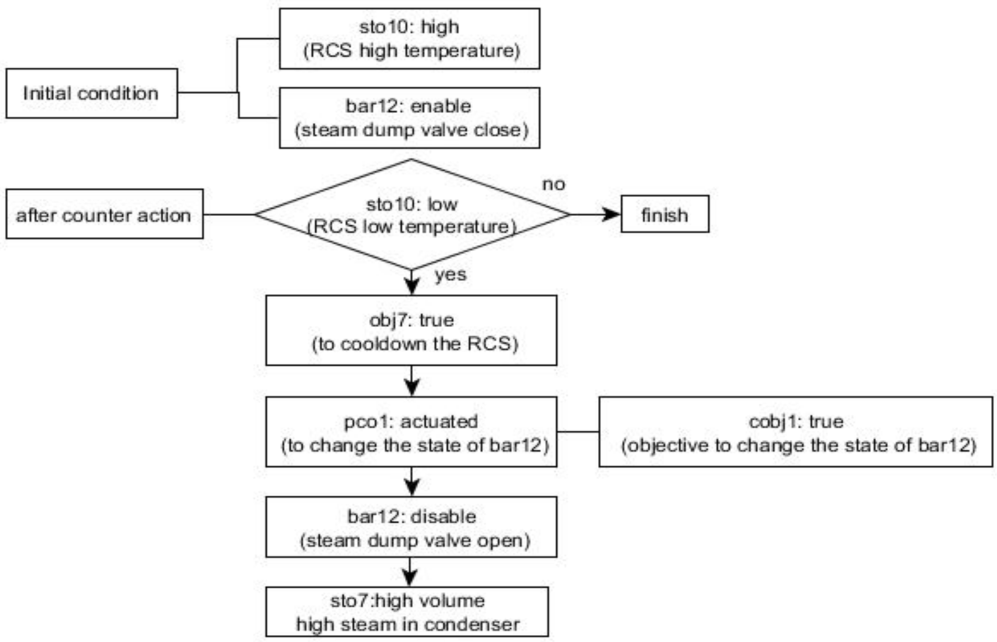


Fig. 8. Impact of RCS cooldown using steam dump valve

Based on the definition states of MFM, the impact of the counteractions can be analyzed using influence propagation rules. Influence propagation means that the change of state of a component will impact the other connected component. This influence will propagate to other components and whole system as well as the objectives of the system. The detail description about the influence propagation rule can be found in [6, 13, 16]. **Figure 8** shows the state change and the influence of the RCS cooldown using steam dump valve operation. The initial condition is indicated by the high temperature level in the RCS (sto10: high) and the steam dump valve is close (bar12: enable). The objective (obj7) of the counter action is to decrease the temperature level of the RCS (sto: low) by opening the steam dump valve (bar12: disable).

5.2. Discussion

The purposes of modeling the operator actions using MFM are to derive the objective of the control actions and to gather information of the impact of the counteractions. The objective of the control action can be easly derived from the objective or the conditional operation of the MFM control function. In case of RCS cooldown using steam dump through steam dump valve operation, the purpose of the control action is to cooldown the RCS by decreasing temperature level of the RCS.

Furthermore, modeling the operator actions is essential for getting information of the impacts of the actions, especially components connected to controlled components. MFM, as a functional modeling based on causal effect relatios, is a useful tool for gathering information about the impact of the control actions. In case of RCS cooldown operation, the components influenced by the control actions derived from **Fig. 7** are summarized in **Table 3**. Therefore, the components influenced by the control action are condenser and auxiliary feedwater system.

Table 4. Components influenced by RCS cooldown operation

Condtional operation	Controlled component	Influenced components
Low volume of sto10 (low temperature of RCS)	bar12 (open the steam dump valve)	High volume of steam in sto7 (condenser) High flow of water in tra14 (auxiliary feedwater system)

Benefits of having the information about the components influenced by the counteractions are to help operators increasing their situation awareness especially in emergency condition and reducing human errors while mitigating the accident and keeping the safe operation of the plant. The information can be added as a desirable feature of computer-based emergency operating procedures [17].

In term of situation awareness, there are three aspects of the benefits:

- before counter action: operators will have clear views and understanding of the

purpose and the impacts of the counteraction
- during counteraction: operators beside considering the controlled component, they will also look at to the influenced components
- after counteraction: operators will monitor the state of impacted components, predict the future state and anticipate the future plant behavior related to the impacted components.

Moreover, related to the reducing of human errors, in case of omission error, since they have enough information about the procedure step, they will follow the procedure step by step without intention to omit or skip one or more procedure steps. While in case of commission error, it will reduce the possibility of operators making mistake in controlling the components to mitigate the accidents.

6. CONCLUSION

Multilevel flow modeling (MFM) is a useful tool to sucessfuly model the operator actions in mitigating accidents following the emergency operating procedures. It is because the MFM is based on causal-effect relation, has control functions and influence propagation features. The results of modeling the operator actions are necessary for determining the purpose and the impact of the counteractions.

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