Mitigation coverage evaluation of passive systems based on causality estimation using Multi-level Flow Model

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Abstract: After the Fukushima accident, the application of passive safety features (PSF) has been importantly suggested for mitigating severe accidents in addition to the conventional active safety features. Nowadays, substantial number of studies related to passive system have been performed and each system has different impact on a nuclear power plant (NPP). For this reason, it is important to use appropriate passive features based on their impacts. Mitigation coverage of PSFs can be importantly used to estimate impact of PSFs. It can be estimated based on the number of accident scenarios, which can be mitigated by applying additional PSFs. In this study, the accident scenarios, which can cause core damage, are firstly defined using fault tree (FT) analysis. Multilevel flow modelling (MFM) is also used to verify completeness of FT. In this study, MFM model is also used to define additional PSFs, which need to mitigate accidents and to determine the number of scenarios that can be mitigated by applying each PSF. As a result, we estimate mitigation coverage of each passive feature as follow: (1) 62.2% of passive secondary cooling system (2) 42.2% of passive high-pressure injection system, (3) 14.6% of passive condenser cooling system.

Keywords: Passive system, Hybrid SIT, Multilevel flow model, mitigation coverage

1. INTRODUCTION

The Fukushima accident was not mitigated properly because there was no proper mitigation systems and strategies against a long-term station black out (SBO). At the time of the accident, the magnitude 9 earthquake produced catastrophic damage to buildings, roads and regional electrical power. The several tsunamis are also produced by earthquake and those flooded building resulting in the loss of emergency diesel powered AC generators and producing condition known as SBO. For these reasons, all active core cooling systems failed to operate. Finally, core was damaged and radioactive materials are released along with the hydrogen explosion [1]. Using this accident as a lesson, the application of passive features has been importantly suggested for mitigating severe accidents in addition to the conventional active safety layer that was designed against design basis accidents (DBAs), because they do not require external energy supplies and can increase the diversity of mitigation techniques [2,3]. For this reason, the combination of passive and active systems has importantly suggested to enhance safety of an existing nuclear power plant (NPP).

Nowadays, substantial number of studies related to passive safety have been performed [4]. Passive systems have their own passive feature and each passive feature has different impact on a NPP. Since passive system uses natural force, the use of passive features is highly dependent on the design of target plant. Therefore, it is important to adopt appropriate passive feature in order to enhance safety of NPP effectively. In addition to use proper passive features, it is also important to define appropriate conditions for using passive feature to develop a novel mitigation strategy that manages the combination of active and passive features in the most efficient manner to overcome the limitation of the conventional accident mitigation strategies that were mainly designed for manipulation of active features. Since use of some passive feature cannot guarantee the long-term mitigation of accident passive feature need to operate in a combined manner with active safety features that are not considered for use in conventional mitigation strategy. That make problem more complicated.

In order to handle this complexity, we suggest a systematic approach, which is multilevel flow modelling (MFM). The MFM is a well-known qualitative modelling methodology for representing complex systems at different abstraction levels of specifications [5]. It has been utilized in several safety critical domains for modelling engineering systems such as nuclear power plants [6] and chemical plants. Since it is difficult to handle all the detailed complexities at the same time at a detailed level, this abstraction methodology has advantages in diagnosing causes of accidents and

finding the counter mitigation procedure when new passive systems are applied in the NPPs [7].

In this paper, MFM can be utilized to define scenarios that cannot mitigated by using conventional mitigation strategies and diagnosis main causes of accidents. This information can be used to find that which passive feature is needed to mitigate accident and the mitigation coverage of suggested passive feature. MFM model can also be used to find optimal combination of mitigation systems including conventional active systems and newly adjusted passive system to mitigate accident properly. There are two approaches to identify the optimal combination for accident mitigation. One is done by the basic feature of MFM, i.e. many-to-many mapping [8]. The second is to search means that has potential to causally influence goal achievement, which can be realized by casual inference of MFM [9].

2. MULTILEVEL FLOW MODELING

2.1 Basic modeling theory

Multilevel Flow Modeling (MFM) is a methodology for graphical modeling of industrial processes on several interconnected levels of means and part-whole relations. The basic idea of MFM is to represent an industrial plant as a system, which provides the means to serve purposes in its environment. MFM has a primary focus on representation of plant goals and functions and provides a methodological way of using those concepts to represent complex industrial plant. The concepts of means-end and whole-part decomposition and aggregation play a foundational role in MFM. Along the means-end relation, a specific end (goal or function) can be realized by means that can be represented by functions in a suitable abstract level. On the other hand, different means-end structures are aggregated in the whole-part dimension to form a complete model. Figure 1 shows its primary symbols which are used for representing goals and functions of industrial process [10].

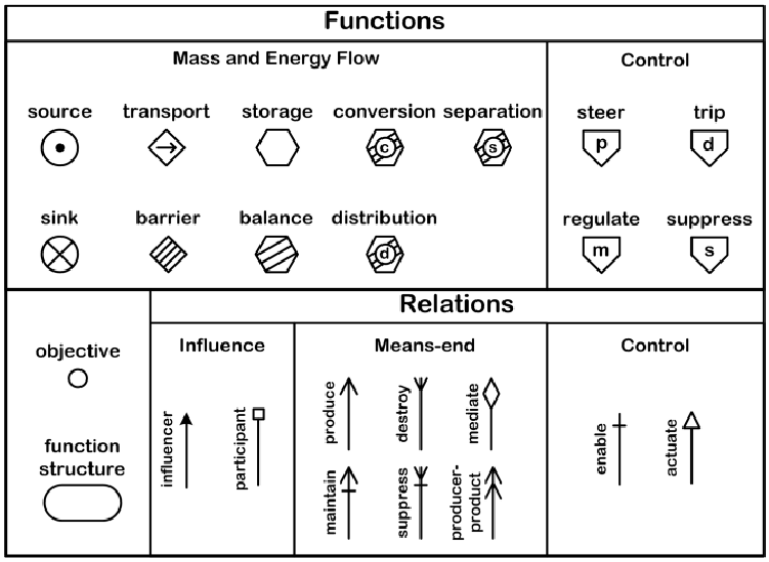


Figure 1 MFM symbols

2.2 MFM reasoning

Since MFM models complex system's objectives and functions with different type of relations, the developed model can be used to analyze the dependency relations between different functions and objectives. Reasoning with MFM models is based on cause-effect relations. MFM is therefore very effective for building knowledge bases for model based expert systems. For this reasoning process, the rule should be defined first to analyze influence propagation systematically.

The cause-effect relations are associated with goal-function and function-function patterns in MFM models. These patterns are defined by influence relations interconnecting the flow functions within the flow structures and the means-end relations making connections between ow structures. For

each of the influence relations and the means-end relations there is a corresponding set of cause-effect relations relating a state of a function or goal with the state of another function or goal in the model. These generic cause-effect relations can be implemented as a rule base system for MFM reasoning. Figure 2 shows example of influence propagation rules [11].

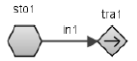
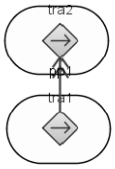
Pattern	Cause	Consequence
 (whole-part)	sto1 high volume sto1 low volume tra1 high flow tra1 low flow	tra1 high flow tra1 low flow sto1 low volume sto1 high volume
 (means-end)	tra1 high flow tra1 low flow tra2 high flow tra2 low flow	tra2 high flow tra2 low flow no consequence no consequence

Figure 2 Examples of influence propagation rules

3. FUNCTIONAL MODELING OF PWR

3.1. System configuration of reference PWR

In this study, advanced power reactor 1400 MWe (APR1400) is used as a reference plant model. APR 1400 is is a standard evolutionary advanced light water reactor in the Republic of Korea developed in 2002. Figure 3 shows the system configuration of an APR 1400 [12].

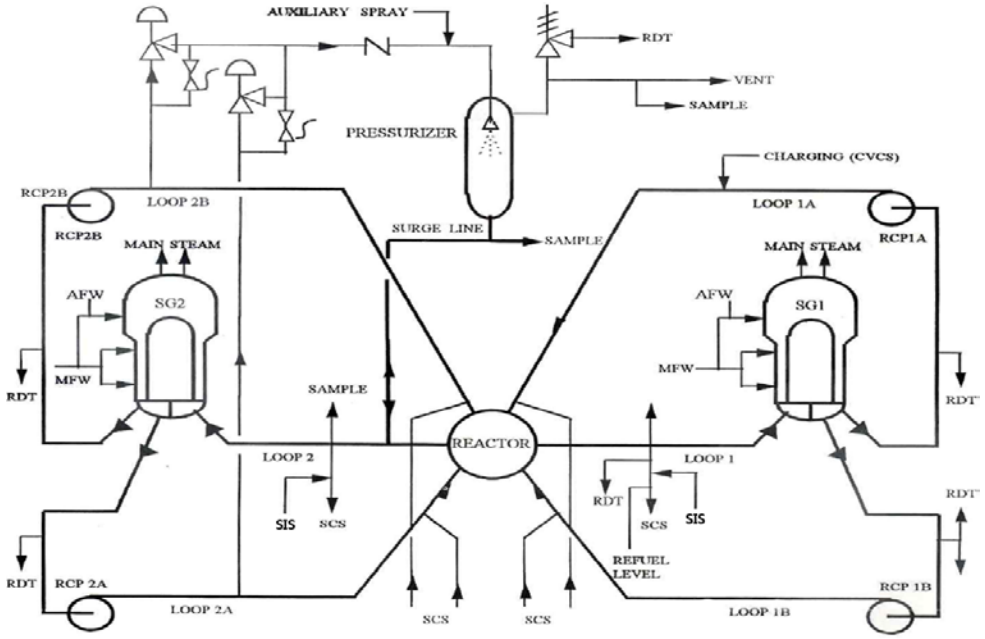


Figure 3 The system configuration of a PWR plant

APR 1400 has similar design configuration compare with other existing pressurized water reactors (PWRs) which has two reactor coolant loops. The one of notable differences is that high and low pressure injection pumps are integrated into one safety injection pump and the pumps which are assigned for shut down cooling system (SCS) and containment spray system (CSP) can also be used for low pressure injection.

3.2. MFM model of PWR

In this study, utilization of passive system is limited only for prevention of core damage. Main objective of this MFM model is defined to maintain heat removal from the coolant in vessel and each component is modeled as a function in the MFM model. Functional relations between functions are modeled based on actual plant design. Figure 4 shows MFM model of PWR plant and systems that are modeled in MFM functional structure are listed as follow: (1) Reactor coolant system, (2) Safety injection system, (3) Main and aux feed water system, (4) Circulating water system, (5) Chemical volume control system, (6) Electricity supply system.

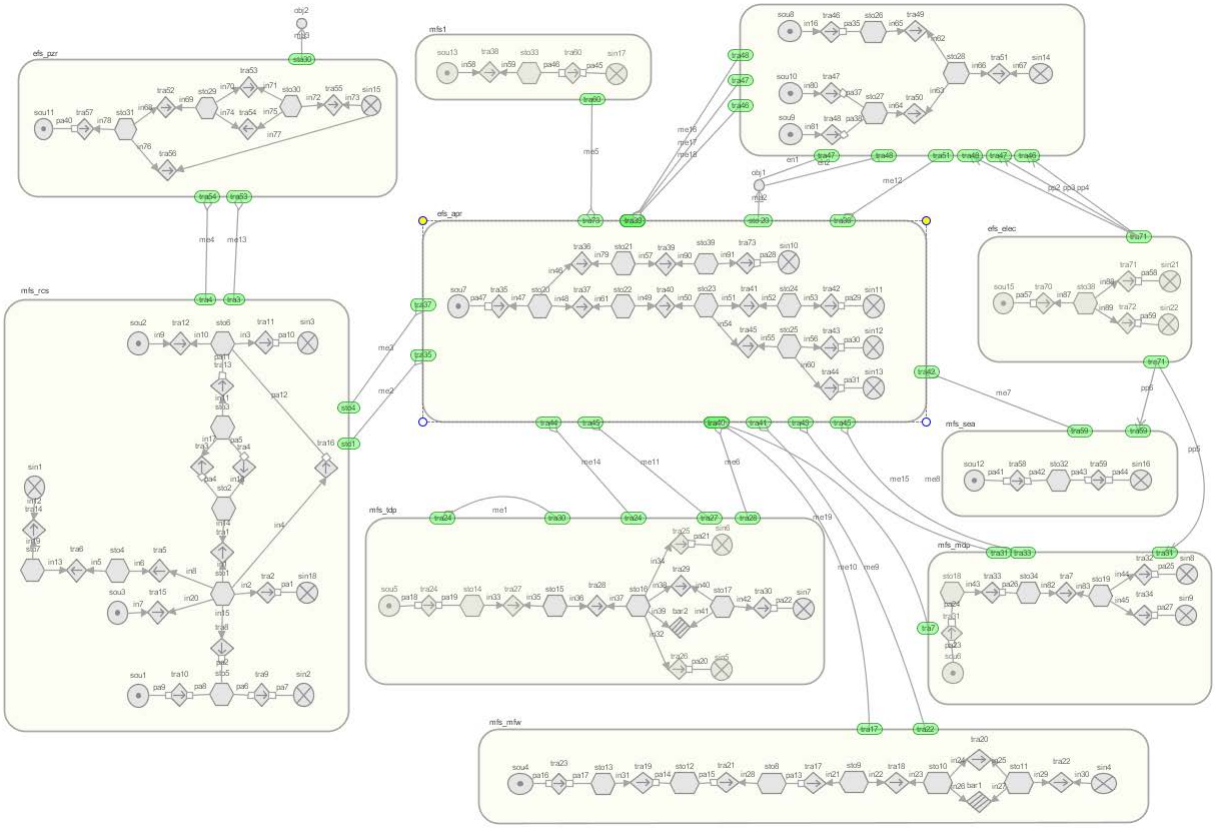


Figure 4 A Complete MFM model of PWR plant

3.2.1 System objective

In this MFM model, there are two objectives: (1) maintain heat removal from coolant in vessel, (2) depressurization of the RCS. First objective is the main objective, which is ultimate goal of mitigation actions. Second objective is the objective for aggressive secondary cool-down. Aggressive secondary cool-down generally performed to use low pressure injection system when high-pressure injection system fails. If second objective is not satisfied, low pressure injection pump is considered to be inoperative because of high-pressure in reactor coolant system (RCS). Those objectives are connected to energy flow of RCS.

3.2.2 Mass and energy flow of RCS

For energy flow in functional structure (efs_apr), the decay heat generated in the reactor core is regarded as the energy source (sou7) and four energy sink can be identified for the heat transport. One (sin10) is the heat sink, which is provided by coolant injection system. In case of APR1400, safety injection system uses water from in-containment refueling water storage tank. For this reason, sin10 represents water inside in-containment refueling water storage tank. Decay heat energy is removed by safety injection through process from tra36 to sin10. The second (sin11) is heat sink that

is provided by main feed water system. In efs_apr, heat removal through main feed water system is assigned from sto23 (= SG) to sin11. Ultimate heat sink for main feed water system is sea water; thus, sin11 represents sea water. Third and fourth (sin12, sin13) is heat sink which is provided by aux feed water system. Since aux-feed system uses water from condensate storage tank, sin12 and 13 represent water inside condensate storage tank. Decay heat removal process using motor-driven aux feed water system is assigned from sto23 to sin12 and heat removal using turbine driven pump is assigned from sto23 to sin13. In MFM model of the RCS, two SG is merged into one because failure of one SG does not have impact on the accident mitigation. In case of the APR 1400, success of heat removal using only one SG can mitigate accident properly. Since decay heat removal rate from core to SG directly links to mass flow rate inside the RCS, mass flow model inside RCS (mfs_rcs) is connected to energy flow of RCS. In mfs_rcs, reactor coolant gas venting valve (tra16) and pilot operated safety relief valve (tra13) are also modeled.

3.2.3 Mass and energy flow of safety injection and feed water systems

In MFM model, mfs_mfw represents mass flow inside main feed water system. mfs_mdp represents aux-feed water system that is operated by motor driven pump. mfs_tdp represents aux-feed water system that is operated by turbine driven pump. In case of the safety injection mass flow structure (mfs_sis), three pumps are independently modeled. Those are safety injection pump, shut down cooling pump and containment spray pump. Those pumps share one injection line and direct vessel injection valve. This design configuration is also modeled in mass flow structure of SIS system. Circulating water system for heat removal from condenser is also modeled in mass flow structure (mfs_sea).

4. SCENARIO DEVELOPMENT FOR USING PASSIVE FEATURE

4.1. Failure cause diagnosis using MFM model

In this section, all abnormal states that cause heat transfer failure from fuel are defined based on causal reasoning process using MFM model. In case of the reasoning process, it is automatically performed using computerized tool, so called MFM suite that is developed by Prof. Lind and his research group [10]. For this process, heat removal failure from coolant in vessel can be modeled by setting high heat amount of water in vessel that is high state of sto_ves in figure 5. All causes can be defined by checking influence propagation starting from high state of sto_ves. Figure 5 shows one of possible propagations and it is summarized as below (“>” means because of).

Objective (false) = high heat amount of water in vessel (sto_ves high) > low heat transfer rate through hot-leg (tra_hotl low) > high heat amount of water in u-tube (sto_sgut high) > low heat transfer rate from u-tube to SG (tra_eva low) > high heat amount of steam in SG (sto_sgs high) > low heat transfer rate from u-tube to aux-feed system (tra_auxv low) > high heat amount of steam in aux-feed water (sto_aux high) > low heat transfer rate through turbine driven aux feed water system (tra_tdp low).

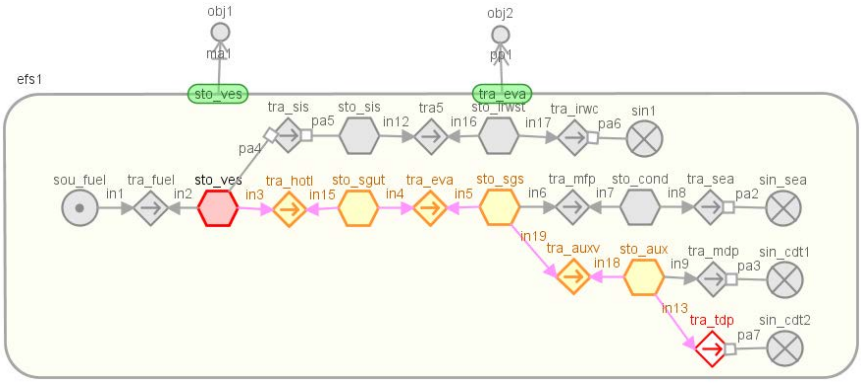


Figure 5 Energy flow structure of reactor coolant system

In reasoning process in MFM, heat transfer failures also link to abnormal mass flow rate based on mean-end relation. Figure 6 show the influence propagation from energy flow structure to mass flow structure using mean-end relation. For example, low heat transfer rate through hot-leg is caused by low mass flow rate in hot-leg and it can be caused by low amount of coolant in vessel. This abnormal state is also caused by five reasons. Those are high mass flow rate to pressurizer (tra 5 high), high mass flow rate through reactor coolant gas venting system (tra_rcgvs high), high mass flow rate through DVI (tra_dvi high), high let down flow rate (tra_letdv high), and low mass flow rate from cold-leg (tra2 low). Each reason is also caused by other reasons. Those reasons can also be defined using causal reasoning which is shown in figure 5. In energy flow structure, all "tra" functions are connected to functions in mass flow structure because failure of heat transfer is directly related with abnormal mass flow rate.

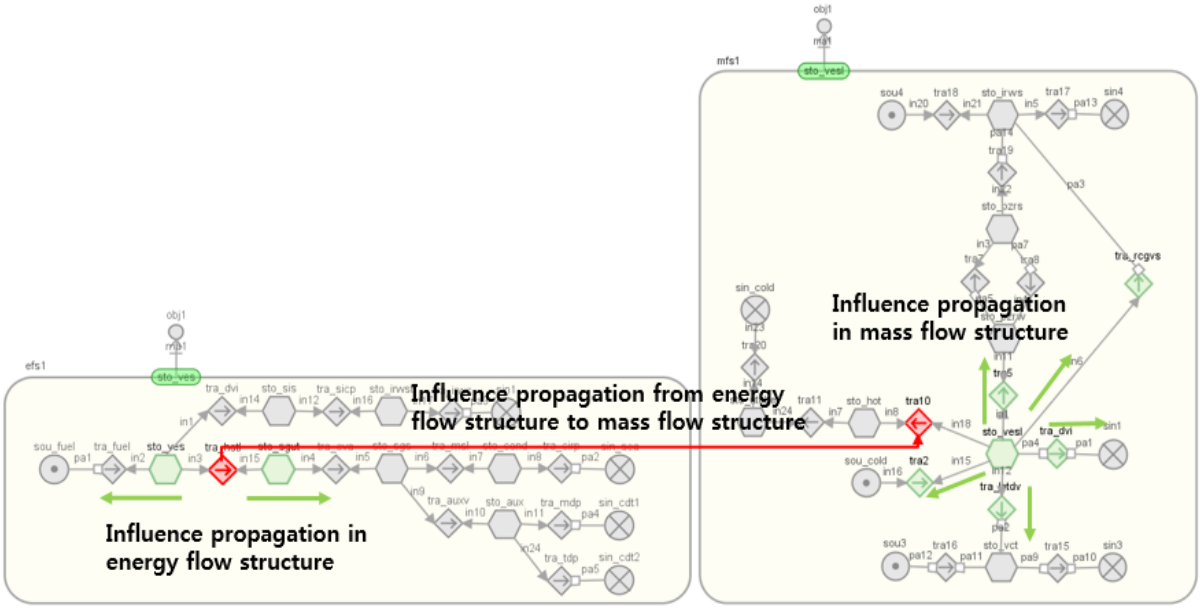


Figure 6 Mean-end relation in MFM model

Based on reasoning analysis using MFM, we can define all reasons that cause heat transfer failure from the fuel as form of abnormal state of components such as low amount of coolant in vessel. In order to develop accident scenarios, these abnormal states should be converted into component failures. In this converting process, abnormal states that are obtained from mass flow structure such as less amount of coolant are only considered. Because heat transfer failure in NPPs are mainly caused by lack of water in reactor coolant system or steam generator. Table 1 show the some examples of converting process. During converting process, causal relation is not considered because it is already considered during reasoning process using MFM model. For example, less amount of coolant in cold leg may be caused by cold leg break or low flow rate from SG u-tube. In case of low flow rate from SG u-tube, this abnormal state is already found in MFM reasoning process (= less amount of water in SG u-tube). Therefore only cold leg break is appropriate accident that represent effect of less amount of coolant in cold leg.

Table 1 Examples of conversion process

Abnormal states		Component failure
Less amount of coolant in cold leg	Converting	Cold leg break
Less amount of coolant in u-tube		U-tube break
High mass flow rate to atmosphere through ADV		ADV stuck open
Low mass flow rate to atmosphere through ADV		ADV stuck close
Low amount of water through MDP		MDP failure

4.2. Scenario development using fault tree analysis

4.2.1 Fault tree development using MFM model

Fault tree analysis is top down analysis in which an undesired state of a system is analysed using Boolean logic to combine series of lower-level events [13]. This method is useful to find combinations, which cause top event failure systematically. It, however, is difficult to guarantee that all events that can be happened in the system are reflected in fault tree model. While MFM reasoning analysis has strength to be able to define all possible reasons that cause dissatisfaction of objective in consideration of interactions between flow of material and energy. It, however, is difficult to develop combination in consideration of and/or combination. For this reason, in this study, fault tree method and MFM method are considered together in order to develop scenario. In fault tree, all basic events are constructed based on component failure information that is obtained by reasoning analysis using MFM model. In addition, flow structures in MFM model are used define structure of fault tree. In order to develop fault tree, we use specific rules as follow.

1. If one branch connects to each function, it is considered as “or” gate.
2. If more than one branches connect to each function, it is considered as “and” gate.
3. Upstream and downstream relation are considered separately.
4. Mean-end relation from functions in mass flow structure is considered separately.

Based on this rules, energy flow function from tra_fuel to tra_eva in figure 5 is converted to fault tree as shown in Figure 7. As aforementioned, “transport” functions that are in energy flow structure are causally related with mass flow functions; thus, all “transport” functions are connected with functions in mass flow structure using “or” gate.

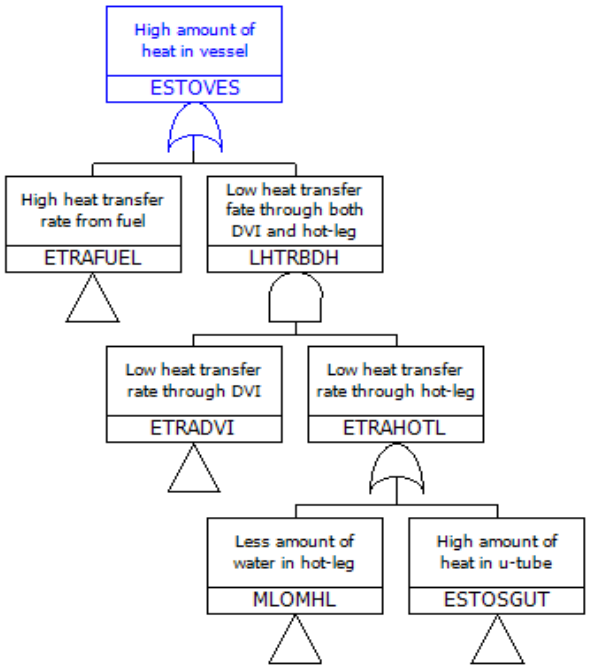


Figure 7 Fault tree model that is developed based on MFM model

4.2.2 Scenario development using fault tree

Based on fault tree model, we can develop all scenarios that cause heat transfer failure from fuel. Figure 8 shows the results of scenario development using fault tree analysis software [14].

Cut Set

1.237e0 / 1.237e0(461 / 461) And

No	Value	F-V	Acc.	BE#1	BE#2	BE#3	BE#4
1	1.000e-1	0.080854	0.080854	DVIB			
2	1.000e-1	0.080854	0.161708	ESOUFUEL			
3	1.000e-2	0.008085	0.169793	MTRAIRWC	SGTR		
4	1.000e-2	0.008085	0.177878	MTRAIRWC	RCGVSS		
5	1.000e-2	0.008085	0.185964	MTRAIRWC	VB		

Figure 8 Scenario development using fault tree model

As a result, 461 scenarios that heat transfer failure from fuel are developed using fault tree model in total. Among those scenarios, 11 scenarios are found as a non-sense scenario, such as ADV stuck open + ADV stuck close + MSSV stuck close. Therefore, 450 cases are considered as scenarios that can be actually happened. Each scenario has information about what is the reason of dissatisfaction of objective. Based on this information, we can decide which passive features are needed to maintain heat removal from fuel. As a result, required passive features are defined as follow: (1) High pressure passive injection, (2) Passive secondary cooling system, (3) passive condenser cooling system. The number of scenario which can be mitigated by adding passive systems are summarized in Table 2. Based on this result, passive secondary cooling system is the most considerable passive system for maintaining heat removal from fuel. Therefore, we have to consider applying passive secondary cooling system into APR1400 in order to increase plant safety.

Table 2 number of scenarios that can be mitigated using additional passive features

Scenarios	Number of scenario	Accident mitigation coverage
Scenarios which cause heat transfer failure from fuel	450	-
The scenarios, which can be mitigated by applying high-pressure passive injection into vessel.	190	42.2%
The scenarios, which can be mitigated by applying passive secondary cooling system	280	62.2%
The scenarios, which can be mitigated by applying passive condenser cooling system	66	14.6%
The scenarios, which cannot be mitigated by applying additional passive systems	103	22.9%

5. ANALYSIS FOR APPLICABILITY OF PASSIVE SYSTEM

In previous section, MFM model is used to defined failure of component which cause failure of heat transfer from fuel. In addition, MFM model also can be used for generating counter-operation strategy when new passive system is added [7]. For this analysis, there are two approaches to identify the alternative means. One is done by the basic feature of MFM, i.e. many to many mapping [8]. Second is to search means that has potential to casually influence goal achievement, which ca be realized by causal inference of MFM. In case of many to many mappings, most systems have the feature of many-to-many mappings of means-end. It can be explained that the same end can be

realized by many alternative means, which can at the same time be used to realize several ends. Dummy structure of many-to-many mapping is shown in Figure 9.

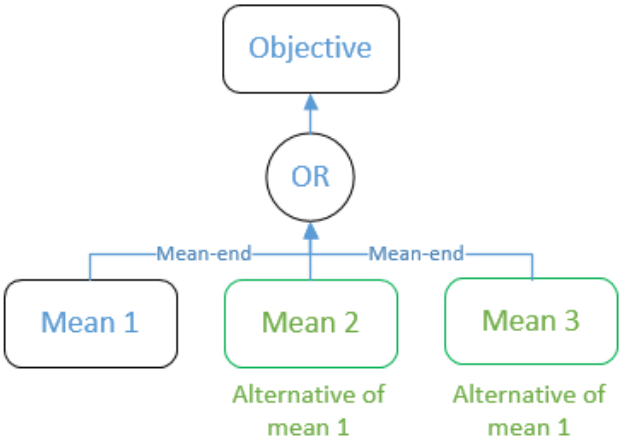


Figure 9 Identifying alternative by many to many mappings

An additional means should not only be used to directly achieve an objective but also be used to enable to use other functions that can affect to objective. In other words, the goal achievement can be caused or influenced by the change of states of some functions. When the objective cannot be satisfied, it should be considered what other functions can change the state of means which can satisfy objective. As shown in Figure 10, this kind of alternative can be identified by using MFM causal inference. In Figure 10, mean 2 cannot originally be used to satisfy objective. It, however, can be used when mean 3 is combined with mean 2.

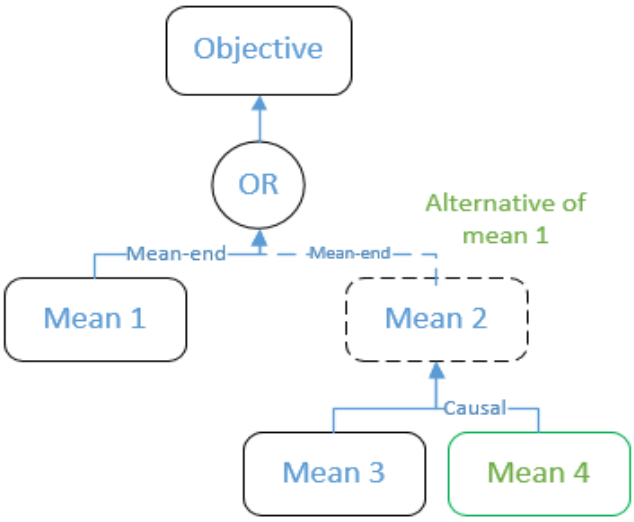


Figure 10 Identifying alternative by causal inference

By using those characteristics of MFM, applicability of passive systems are analyzed based on scenarios that are obtained from fault tree analysis. As aforementioned in previous section, high-pressure passive injection system is the one of considerable passive system to increase plant safety. And it is also easy to install into existing NPP. Therefore, hybrid safety injection tank (H-SIT) is considered as a case study.

H-SIT was invented to passively inject coolant into the RCS under any pressure condition without depressurization [15]. This system can be available for any PWR which has safety injection tanks or accumulators. In low-pressure accidents such as medium and large-break loss of coolant accidents (LOCA), the H-SIT system injects water using the pressure from nitrogen gas as a conventional safety-injection tank. In high-pressure accidents, the H-SIT system injects water using gravitational force; the pressure of each H-SIT is equalized with RCS pressure through equalizing

pipes when the equalizing valve is opened by the operator; thus, allowing the H-SITs to inject water by gravity. Figure 11 shows conceptual layout of H-SIT system.

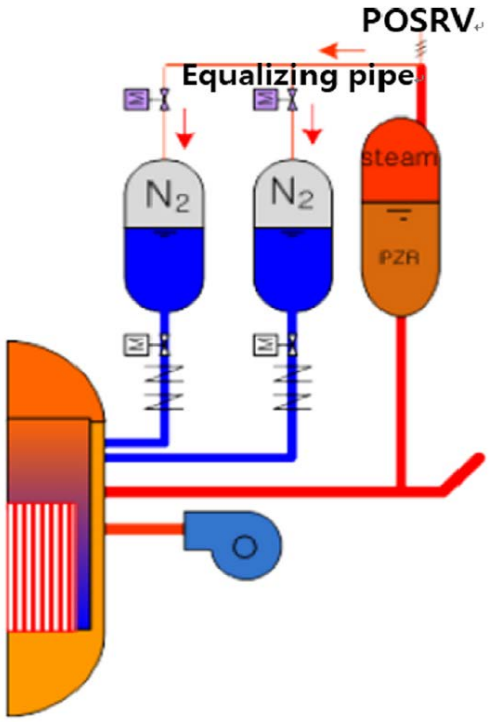


Figure 11 Conceptual layout of H-SIT system

As a first step, scenarios which are defined using fault tree analysis are are applied to the MFM model. Since those scenarios are the combination of objective failure, objective becomes unsatisfactory. As a second step, suggested passive system such as H-SIT is added into MFM model. Then we can find whether or not objective is satisfied again by reasoning analysis using MFM model. If we perform same process for all scenarios, we can estimate mitigation coverage of suggested passive system. In addition, we can find that what are the reasons that added passive system cannot satisfy the objective. Based on this information, we can also decide whether or not there are counter operation operation strategies. Figure 12 shows one of case study how conditions that can be mitigated by H-SIT are decided using MFM model. In this case study, RCGVV stuck open and SIP inlet valve stuck close are modeled as a failure scenario (the functions that are colored in red fail). Because of RCGVV stuck open, mass flow rate through RCGVV is high (tra16 high). Because of tra16 high, inventory in vessel decrease (sto1 low). This abnormal state results in low mass flow rate through hot-leg (tra5 high). Heat transfer rate through hot-leg also decreases (tra19 low). In this situation, decay heat removal using coolant injection with SIPs also impossible due to stuck close of SIP inlet valve (bar 1 blocked). Low pressure injection pumps cannot be used due to high-pressure inside the RCS (dissatisfaction of obj2 that is depressurization of the RCS). For these reasons, decay heat cannot be removed with conventional mitigation systems. Therefore, objective become unsatisfactory using conventional mitigation strategy.

If H-SIT system (mfs_hsit) is applied, decay heat can be removed without core dry-out even if RCGVV stuck open (tra30 high). Because of heat removal through the H-SIT and RCGVV stuck open, RCS can be depressurized safely (obj2 satisfied). For this reason, low-pressure injection pumps can be used to inject water to the RCS (tra28 and 29 high). Therefore, decay heat can be removed by safety injection with low-pressure injection pumps for a long time (tra 18 high). Based on these analysis results, we can develop detailed mitigation strategy using H-SIT system against LOCA with failure of all safety injection pumps. If same process are repeated for all possible accident scenarios, we can defined number of scenarios that can be mitigated using the H-SIT. That represents mitigation coverage of H-SIT system.

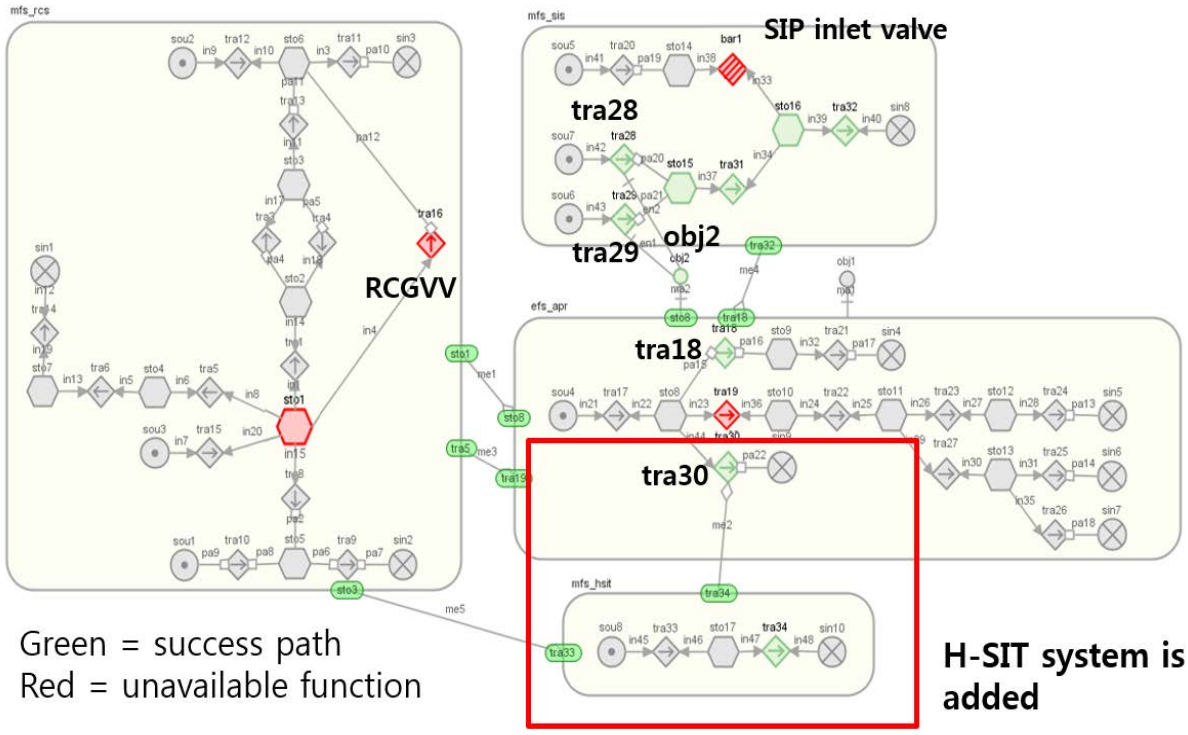


Figure 12 Analysis for finding conditions, which can be mitigated by H-SIT system MFM model

As a result, we estimate that 183 scenarios can be covered by using H-SIT system. Mitigation coverage of H-SIT system is 40.6%. The representative scenarios, which can be mitigated using H-SIT are as follow: (1) Partial coolant loss accident such as SGTR + all safety injection pump failure, (2) LOCA + high pressure injection pumps failure. In case of scenario 1, the void in vessel prevent natural circulation inside vessel thus secondary cooling system cannot be used to remove heat. If H-SIT is added, it can be used to make up core inventory. Then operator can remove heat using secondary cooling system. If LOCA is occurred, operator inject coolant into vessel for feed and bleed operation. For feed and bleed operation, however, high pressure injection pump can only be used because operator need depressurization too long because of low maximum injection pressure of low pressure injection pump [16]. It causes core depletion during depressurization. If H-SIT is added, it can be used to make up core inventory during depressurization because it can inject coolant under high-pressure condition. For this reason, low pressure injection pumps can be used for feed bleed operation with H-SIT system. We can also estimate that H-SIT system cannot be used in follow situations using MFM reasoning analysis: (1) DVI break, (2) Safety injection head break, (3) POSRV stuck open.

6. CONCLUSION

Based on the MFM model, we can systematically develop the fault tree and we can guarantee of perfection of FT model. Since MFM reasoning analysis has strength to be able to define all possible reasons that cause dissatisfaction of objective in consideration of interactions between flow of material and energy, the weakness of FT method can be overcome in combination of MFM method. MFM method can be also used for generating counter-operation strategy when new passive system is added. By this process, we can easily estimate applicability of passive systems based on scenarios that are obtained from fault tree analysis. As a result of this analysis, passive secondary cooling system is the most efficient passive feature to enhance plant safety. It, however, is difficult to construct into existing NPP. In case of passive high-pressure injection system, it has high mitigation coverage and it is easy to install into conventional NPP. H-SIT is one of possible candidate for passive high-pressure injection system and it has accident mitigation coverage of 40.6%. Therefore, mitigation strategy development of H-SIT is recommendable to increase plant safety under situations as follow: (1) Partial coolant loss accident such as SGTR + all safety injection pump failure, (2) LOCA + high pressure injection pumps

failure. In order to develop detailed mitigation strategy, thermos-hydraulic analysis will be performed for a future work to define optimal parameter, such as operation timing and number of tanks that should be operated together to supply enough amount of water from tank. If detailed mitigation strategy that include operation of H-SIT is adopted, it will effectively increase plant safety.

Acknowledgements

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