Mitigation coverage estimation of passive systems using causal reasoning analysis with Multi-level Flow Model

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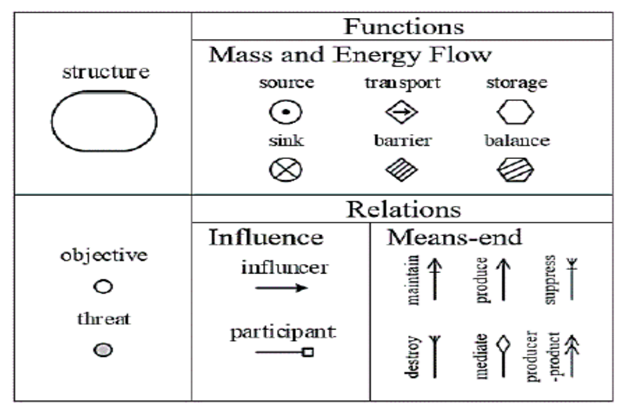
Multilevel flow modeling

- Multilevel flow modeling (MFM) is a qualitative modeling methodology for representing complex systems at different abstraction level.
  - It represents goals and functions of industrial process involving interactions between functions of material and energy.

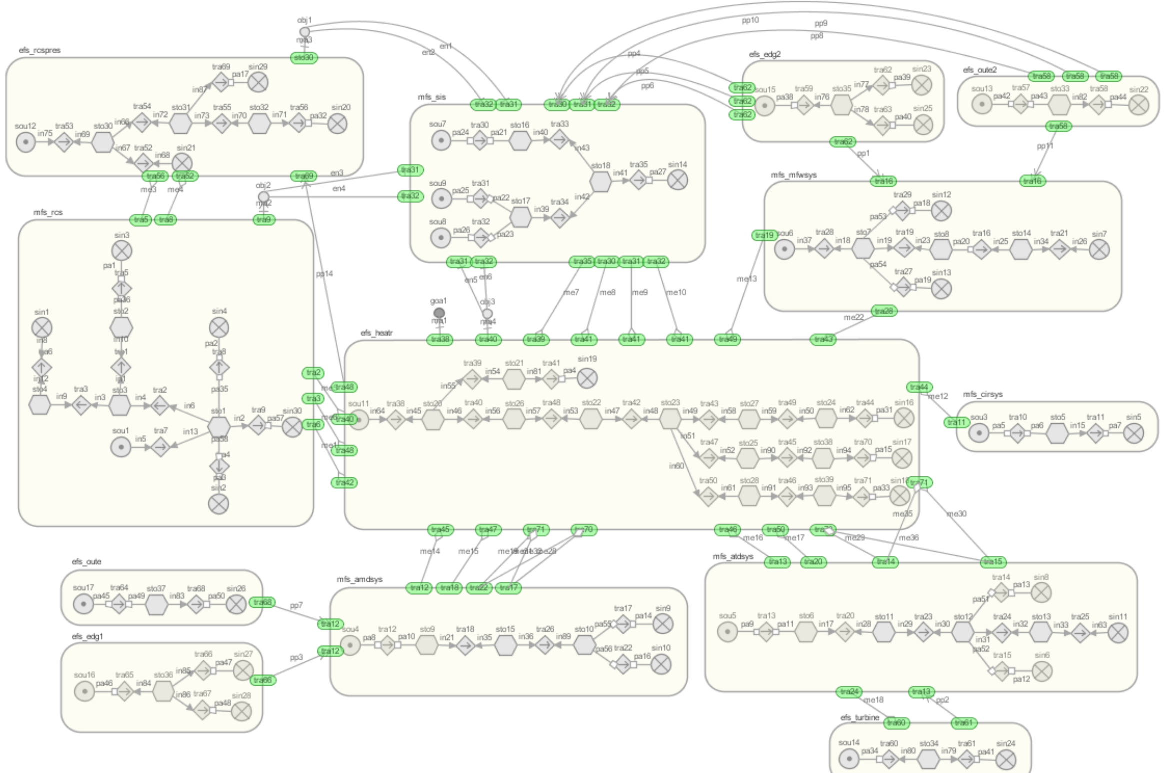
- Functional modeling framework has hierarchical modeling capability to handle a complicated engineering system.
  - Since it is difficult to handle all the complexities together at a detailed level, this abstraction methodology has advantages to simplify complex systems systematically at different abstraction level.

Syntax of MFM method



MFM modeling for PWR

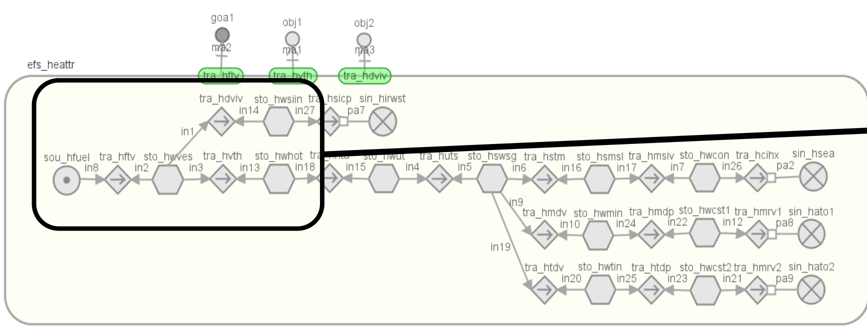
- Systems considered in MFM model
  - Reactor coolant system
  - Safety injection system
    - High-pressure injection system
    - Low-pressure injection system
  - Main & Aux feed water system
    - Motor-driven system
    - Turbine-driven system
  - Circulating water system
  - Electricity supply system
  - In-containment refueling storage tank

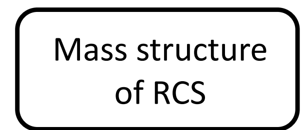


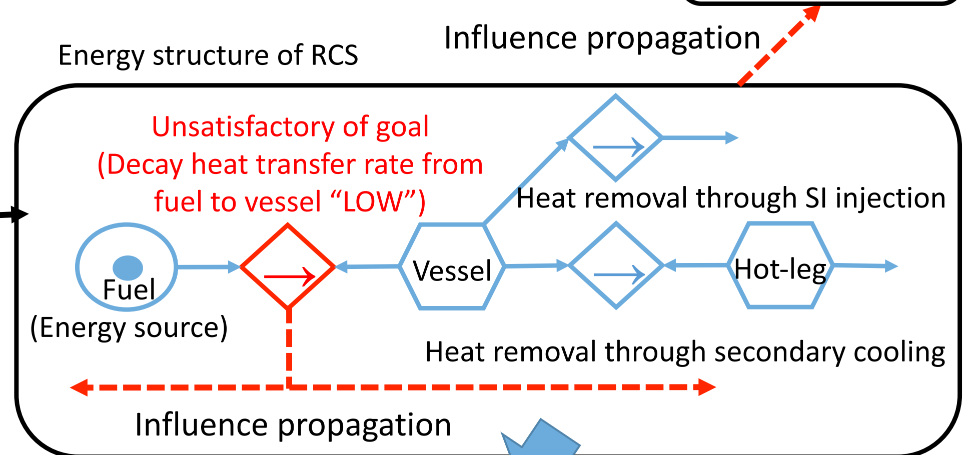
MFM model of PWR

Causal inference analysis

- In the MFM model, the causal relations between the components in the NPP can be expressed in linguistic representation.
- All causes (= abnormal states) that induce unsatisfactory goal of MFM (= maintain decay heat removal) are defined by causal inference analysis.





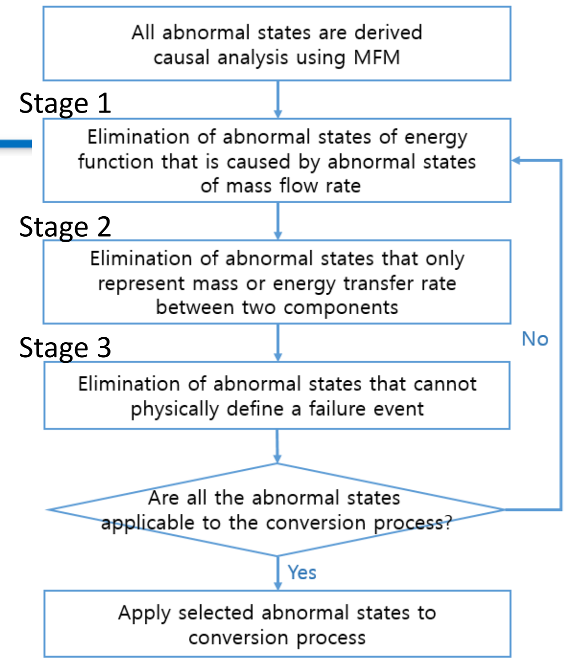


Starting point

Causal inference propagation in MFM model		Heat generation from fuel low	Decay heat transfer rate from fuel to vessel low	High heat accumulation in water of vessel	Low heat transfer rate from vessel to hot-leg	High heat accumulation in water of hot-leg	…

Influence propagation

Conversion & Elimination process



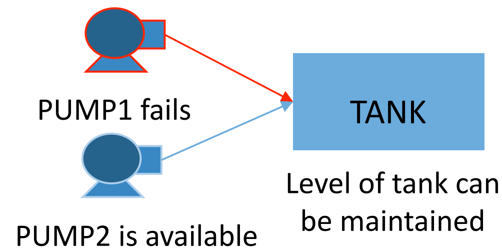
- Conversion process: from abnormal states to failure events
  - Only abnormal states can be obtained as the results from the MFM analysis.
  - Some abnormal states derived from the MFM are only converted into failure events.
- An elimination process has been additionally proposed to determine the abnormal states that can be applied to the conversion process. (= 3 stages)

- Based on results of failure mode and effect analysis, two types of failure events are considered.
  - Abnormal operation of components
  - Break of components

Abnormal states		Failure events
Less amount of coolant in cold leg	**Converting** →	Cold leg break
Low mass flow rate through MSSV		MSSV stuck close
High mass flow rate to atmosphere through ADV		ADV stuck open

An example of conversion process

Development of accident scenarios

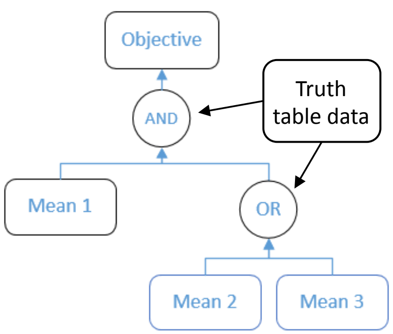


- For redundancy design, the truth tables are applied to MFM to decide whether or not target functions are in abnormal condition due to a failure of some adjacent functions.
  - These tables are developed based on success criteria of systems and TH analysis results.
- Boolean equation is utilized to develop all combinations of failure events that induce decay heat removal failure based on MFM model and truth tables.

Truth table

V	FALSE	TRUE	PUMP2
FALSE	FALSE	TRUE	
TRUE	TRUE	TRUE	TANK
PUMP1			

Combination that causes low level of tank can be defined (Pump1 failure and Pump 2 failure)



Solving Boolean equation

Objective failure

$$= \overline{mean\ 1} + \overline{mean\ 2} * \overline{mean\ 3}$$

scenario	Combinations of failure
# 1	$\overline{\textbf{mean 1}}$
# 2	$\overline{\textbf{mean 2}}$, $\overline{\textbf{mean 3}}$

Development of accident scenarios

- After solving Boolean equation with logic diagram, 478 failure combinations are defined as possible accident scenarios which cause decay heat removal failure.

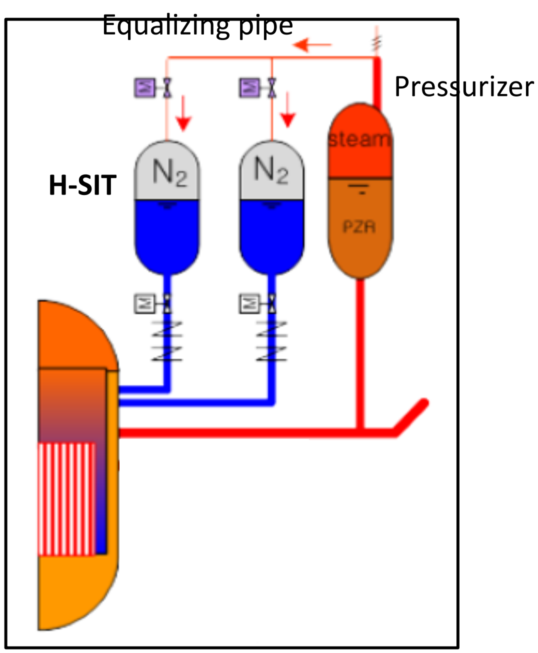
- Group of all defined accident scenarios
  - Group 1 (High-pressure injection failure + secondary cooling system failure), 415 scenarios
  - Group 2 (High-pressure injection failure + loss of coolant accident (LOCA)), 44 scenarios
    - Unlimited LOCA (e.g. hot-leg break), 39 scenarios
    - Partial LOCA (e.g. steam generator tube rupture), 5 scenarios
  - Group 3 (SBO + turbine driven secondary cooling system failure, 10 scenarios
  - Group 4 (Station black out (SBO) + LOCA), 9 scenarios
    - Unlimited LOCA (e.g. hot-leg break), 8 scenarios
    - Partial LOCA (e.g. u-tube break), 1 scenarios

#	Failure 1	Failure 2	Failure 3	Failure 4
1	DVI valve stuck open	POSRV stuck open	-	-
2	DVI line break	RCGVS stuck open	-	-
3	DVI line break	U-tube break	-	-
…	…			
476	SIP failure	MDP failure	Main feed water isolation valve stuck close	Turbine break for TDP
477	SIP failure	MDP failure	Main feed water pump failure	TDP failure
478	SIP failure	MDP failure	Main feed water pump failure	Turbine break for TDP

Accident scenarios developed by MFM analysis (Result)

Application of H-SIT system

- The hybrid Safety Injection Tank (H-SIT) was invented to passively inject coolant into a reactor coolant system (RCS) under any pressure condition without depressurization

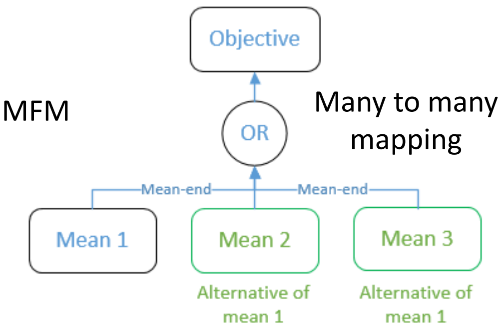


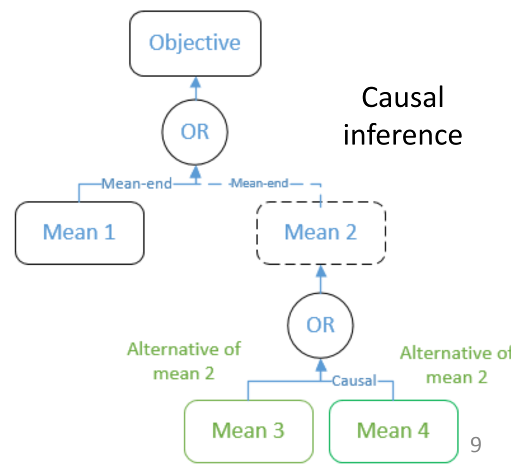
- In low-pressure accidents, such large-break loss of coolant accident, the H-SIT system injects water using the pressure from nitrogen gas as a conventional accumulators in NPP.

- In high-pressure accidents, it provides inventory make-up by gravitational force after the pressure of the H-SIT equalizes with RCS pressure through equalizing pipe.

Feasibility analysis of the H-SIT

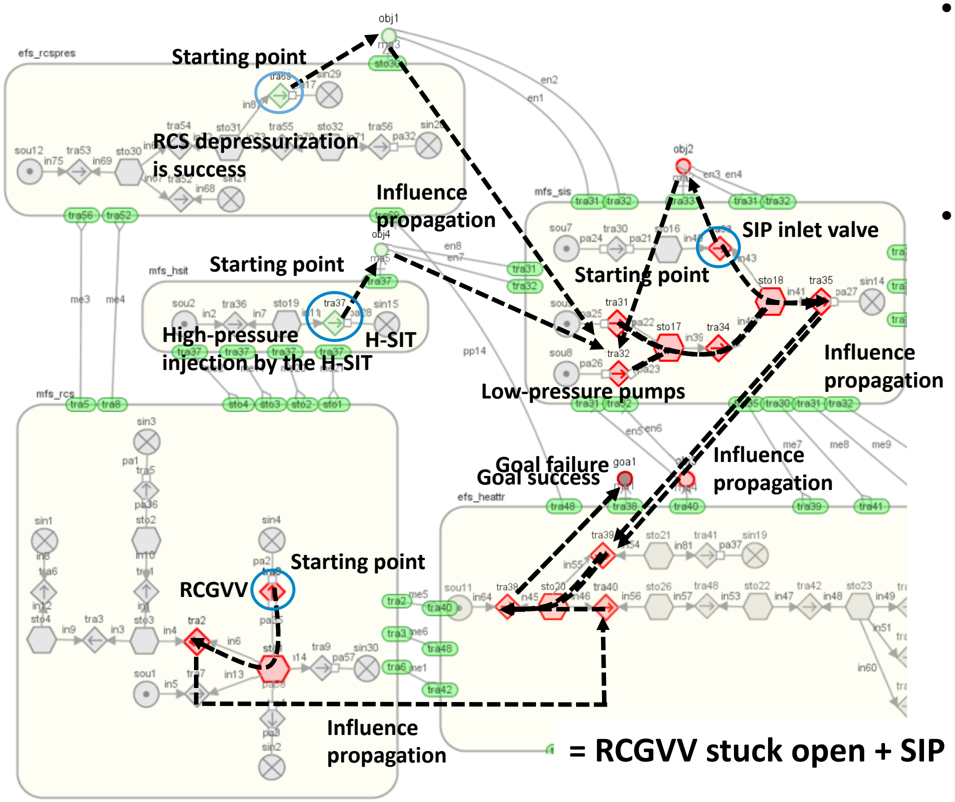
1. MFM model is reconstructed considering the application of the H-SIT.
2. Accident scenarios that are obtained from previous analysis are inserted into the modified MFM model.
3. Alternative ways (= counter-measure) to satisfy the object are identified in consideration of two approaches.
    - Many to many mapping
        - Many to many mapping can be explained that the same end can be realized by many alternative means.
    - Causal inference
        - Additional means not only be used to directly achieve an objective, but also be used to enable other functions, which can affect objective.
4. Mitigation coverage estimation of the H-SIT.
    - Mitigation coverage $= \frac{\text{Number of scenarios which can be mitigated by the H–SIT}}{\text{All accident scenarios}}$





Example of H-SIT application

- Consequence analysis using MFM



- Reflection of predefined accident scenario to MFM model
  - Reactor coolant gas venting valve (RCGVV) stuck open + SIP inlet valve stuck close
- Determination of alternative mitigation ways with the H-SIT by causal reasoning in MFM model
  - High-pressure injection from H-SIT is applied (tra37)
  - RCS depressurization (obj1) keeps success.

  >> Low-pressure safety injection (LPSI) pumps can be used to inject water into the vessel (tra31 and tra32 are high).

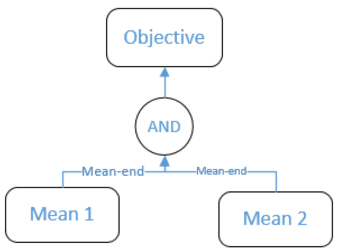
  >> Continuous decay heat removal is possible (tra38 is high).

  >> State of goal changes from failure to success.

= RCGVV stuck open + SIP inlet valve stuck close can be mitigated by applying the H-SIT

Application of Boolean equation

- Based on consequence analysis results from MFM analysis, Boolean equation is recalculated to determine the mitigated accident scenarios.

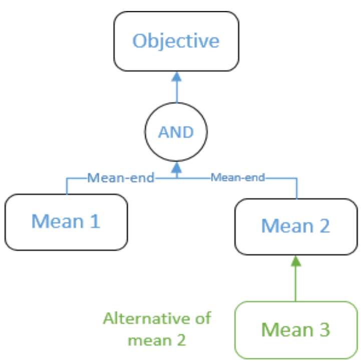


Solving Boolean equation

Objective failure

$= \overline{mean\ 1} + \overline{mean\ 2}$

scenario	Cut set
# 1	$\overline{mean\ 1}$
# 2	$\overline{mean\ 2}$



Solving Boolean equation

Objective failure

$= \overline{mean\ 1} + \overline{mean\ 2} * \overline{mean\ 3}$

scenario	Cut set
# 1	$\overline{mean\ 1}$
# 2	$\overline{mean\ 2}$, $\overline{mean\ 3}$

- Scenario 2 in table 1 can be covered by applying mean 3.
- In same way, all scenarios which are mitigated by applying the H-SIT can be identified.
- Mitigation coverage can be estimated based on total number of mitigated scenarios.

Analysis results

- Mitigation coverage estimation of the H-SIT
  - Group 1 (High-pressure injection failure + secondary cooling system failure)
    - 249 scenarios can be mitigated among 415 scenarios, **Mitigation coverage = 60%**
  - Group 2 (High-pressure injection failure + LOCA)
    - (Unlimited LOCA), 24 scenarios can be mitigated among 39 scenarios, **Mitigation coverage = 61.5%**
    - (Partial LOCA), 3 scenarios can be mitigated among 5 scenarios, **Mitigation coverage = 60%**
  - Group 3 (SBO + turbine driven secondary cooling system failure), 10 scenarios
    - 10 scenarios can be mitigated among 0 scenarios, Mitigation coverage = 0%
  - Group 4 (SBO + LOCA)
    - (Unlimited LOCA), 8 scenarios can be mitigated among 0 scenarios, Mitigation coverage = 0%
    - (Partial LOCA), 1 scenarios can be mitigated among 1 scenarios, **Mitigation coverage = 100%**

Mitigation strategies with the H-SIT

Group 1 (High-pressure injection failure + secondary cooling system failure)	Development of feed and bleed (F&B) mitigation strategy with H-SIT under low-pressure condition
Group 2 (High-pressure injection failure + unlimited LOCA)	Development of long-term mitigation strategy with SCP and H-SIT
Group 2 (High-pressure injection failure + partial LOCA), Group 4 (SBO + partial LOCA)	Development of long-term mitigation strategy with secondary cooling system and H-SIT under SGTR
Group 3 (SBO + turbine driven cooling system failure) Group 4 (SBO + unlimited LOCA),	Development of mitigation strategy for coping time extension with H-SIT

END