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Analysis of Initiating Events for SMART using Heat Balance Fault Tree Method

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1. Introduction

SMART (System-integrated Modular Advanced ReacTor), an integral type of PWR with a capacity of 365MWth, has been developed for multiple purposes such as seawater desalination, ship propulsion, and district heating in Korea since the early 1990s. The basic design of SMART was completed in 2002 [1]. Since SMART's basic design concept has been established, the introduction of a passive safety system such as PRHRS (Passive Residual Heat Removal System), PSIS (Passive Safety Injection System), or PCCS (Passive Containment Cooling System) has reduced the dependence of the electrical system and human error, and the safety of SMART has improved. A SMART PSA was proposed that reflects the design change of SMART owing to above design change of SMART to improve the safety. In this paper, as part of a SMART PSA, the HBFT (Heat Balance Fault Tree) method is used for the selection of all possible initiating events in SMART and is briefly introduced. The initiating event screening results of SMART and a brief introduction of the HBFT method are covered in the next section. Owing to the absence of a commercial nuclear power plant of a similar type and the operating experience of SMART, PSA reports of a commercial nuclear power plant are used for verification and comparison with the selected initiating events using the HBFT method. Further study and an application plan are covered in the conclusion.

2. Methods and Results

2.1 Methods for Identification of Initiating Events

Empirical evaluation methods such as an analysis of the operating experience, a review of a commercial nuclear power plant PSA report of a similar type, and logical evaluation methods such as FMEA (Failure Mode and Effect Analysis), MLD (Master Logic Diagram), HBFT (Heat Balance Fault Tree) are applied for screening potential initiating events of NPPs (Nuclear Power Plants). Such logical evaluation methods reduce potential errors that can occur during initiating event selection and can screen initiating events that are likely to be ignored. General logical evaluation methods are as follows [2]:

- Master Logic Diagram (MLD)
- Heat Balance Fault Tree (HBFT)
- Classification of Historical Initiating Events
- Comparison with Other PRAs
- Feedback from Other Parts of the Risk Model
- Failure Modes and Effects Analysis of Plant Systems (FMEA)

The MLD and HBFT methods are mainly used in the screening of initiating events. The classification of Historical Initiating Events, Comparison with Other PRAs, and Feedback from Other Parts of the Risk Model are used as independent checks. FMEA (Failure Modes and Effects Analysis of Plant Systems) is mainly used for initiating events that can occur in the support system. The HBFT method is discussed in detail in the next section.

2.2 HBFT (Heat Balance Fault Tree)

HBFT is a logical evaluation method for screening the initiating events in NPPs by understanding the thermal imbalance occurring among the thermal boundaries of NPPs, and deductively tracking the causes of thermal imbalance. The HBFT method is generally used for the MLD and empirical evaluation methods. Screening the initiating events using a top-down logic development method is a common feature of MLD and HBFT, but their top events are different. The top event of the MLD method is a "significant release of radioactive material" and the top event of the HBFT method is a "thermal imbalance occurring due to an initiating event." There are slight differences in the type and granularity of the selected initiating events because of the difference in their top event. Generally, the HBFT method can screen initiating events more than the MLD method. In general, a nuclear power plant consists of a reactor, a primary coolant system, a secondary coolant system, and a turbine-generator system. Such systems maintain a thermal equilibrium state and share the heat flow through some components and systems. Fig. 1 shows the general heat transport path in NPPs.

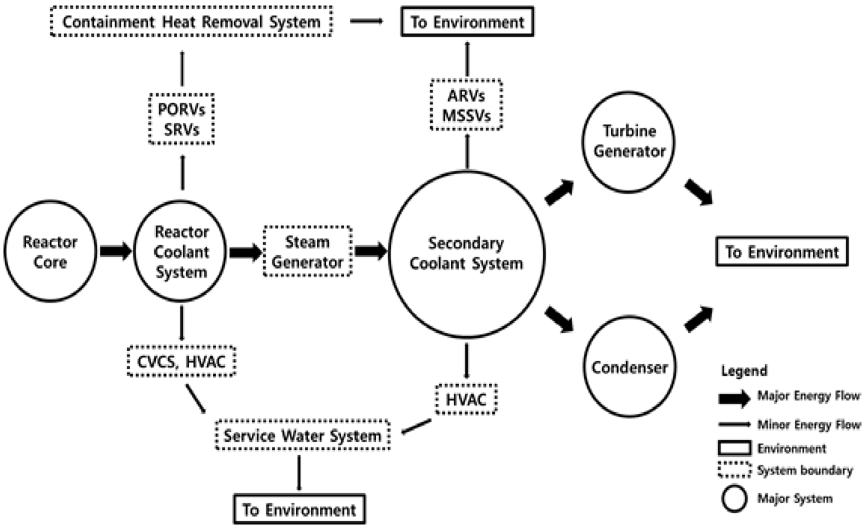

Fig. 1. Heat transport path diagram

The main heat transport is achieved from the reactor core to the primary coolant system, and from the primary system coolant to the secondary coolant system through the steam generator. It is directly released or converted into electrical energy through the turbine-generator system. In addition, the additional heat transfer path includes heat loss and a bypass through the bypass system. In the HBFT method, it is assumed that the thermal imbalance between the thermal systems cause a transient state in the plant. Based on this assumption, thermal boundaries are defined, and initiating events that can cause a thermal imbalance between the defined thermal boundaries are selected. Basically, the thermal boundaries considered in the HBFT method are as follows [2]:

- Energy transfer between the core and RCS
- Between the RCS and SCS
- Between the SCS and plant output

Fig. 2 shows the HBFT for the screening initiating events of SMART based on an AIMS-PSA work station [3]. The top event of the HBFT is a “thermal imbalance occurring due to an initiating event” and the development of logic starts from the top event of the HBFT.

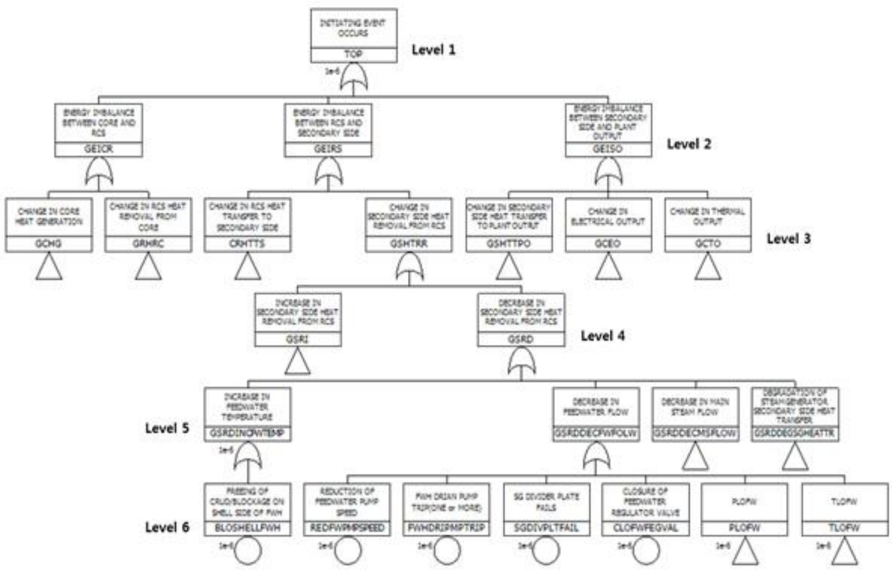

Fig. 2 HBFT (Heat Balance Fault Tree)

In the HBFT method, the development of logic is divided into six stages, and the stage 6 is generally the final stage, but there may be unchecked initiating events. The stages of the HBFT are slightly different depending on the purpose of the analysis and the degree of fragmentation. For each step, for the development of logic, the cause of the thermal imbalance and the thermal system in which the thermal imbalance occurs is defined at the top event of each step.

In the first step of the HBFT, the top event of the HBFT is defined. This is the "thermal imbalance occurring due to an initiating event."

In the second step of the HBFT, thermal boundaries that can incur a thermal imbalance are defined. The HBFT for SMART is the defined thermal boundaries such as the energy transfer between the core and RCS (Reactor Coolant System), between the RCS and SCS (Secondary side Coolant System), and between the SCS and plant output.

In the third step of the HBFT, thermal imbalances that occur at the thermal boundaries defined in step 2 are selected. In the 4th step of the HBFT, the increase/decrease of the phenomena selected in step 3 is defined. In the 5th step of the HBFT, the cause of the increase/decrease in step 4 is defined. In the 6th step of the HBFT, the initiating events for the cause found in step 5 are defined. The top events of each step are summarized in Table 1.

Table 1: Top event of HBFT

Level	Top event
Level 1	Thermal imbalance occurs due to initiating events
Level 2	Define system boundaries where an imbalances occur (e.g., dnergy imbalance between RCS and SCS)
Level 3	It is shown that the source of each imbalance can originate on either side of the energy transfer points identified in level 2. (e.g., change in SCS heat removal from RCS)
Level 4	It is shown that each change identified at level 3 can start out as an increase or a decrease in energy generation or transfer. (e.g., decrease in SCS heat removal from RCS)
Level 5	Define cause of phenomenon of previous level (e.g., decrease in feedwater flow)
Level 6	Define initiating events that cause phenomenon of previous level. (e.g., feedwater line break)

2.3 Selection of Initiating Events for SMART

The potential initiating events of SMART are selected using the HBFT method. Among the selected initiating events, the initiating events for which the progress of the events are expected to be similar are grouped and shown in Table 2.

Table 2: List of initiating events of SMART

LOCA (Loss of Coolant Accident)	
Category	Initiating Event
SLOCA	SLOCA (In CTMT)
	ADS Line Break
	Improper SV or RV Open (PZR)
	Improper ADS Operation
Isolable LOCA	Isolable LOCA
ISLOCA	ISLOCA (Interfacing LOCA)
RVR	RVR (Reactor Vessel Rupture)
RCPE	RCPE (Reactor Coolant Pump Ejection)
SGHR	SGHR (Steam Generator Header Rupture)
SGTR	SGTR (Steam Generator Tube Rupture)
Transients	
Category	Initiating Event
LOOP	LOOP (Loss of Offsite Power)
PLOCCW	PLOCCW (Partial Loss of Component Cooling Water)
TLOCCW	TLOCCW (Total Loss of Component Cooling Water)
LOKV	LOKV (Loss of 4.16kV AC Bus)
LODC	LODC (Loss of 125V DC Bus)
LSSB	LSSB (Large Secondary Side Break MSIV Downstream)
SLBU	SLBU (Steam Line Break MSIV Upstream)
	Opening of Atmospheric Relief Valves (ARVs)
	Opening of Main Steam Safety Valves (MSSVs)
	Opening of Turbine Control Valves (TCVs)
	Opening of Turbine Bypass Valves (TBVs)
TLOFW	TLOFW (Total Loss of Feedwater)
	Feedwater Line Break
	LOCV (Loss of Condenser Vacuum)
PLOFW	PLOFW (Partial Loss of Feedwater)
	Inadvertent Opening of FWH Bypass Valve
	Feedwater Isolation Valve Closure
	Closure of Feedwater Regulator Valve
	Closure of One or More MSSVs (Main Steam Safety Valves)
	Feed Regulator Valve Failures
	Reduction of Feedwater Pump Speed
	FWH Drain Pump Trip (One or More)
ATWS	ATWS (Anticipated Transient Without Scram)
GTRN	All transient events other than those classified separately

3. Conclusions

In this paper, the HBFT (Heat Balance Fault Tree) method has been applied and briefly introduced to select initiating events that can occur in SMART. Since various methods for selecting initiating events have their advantages and disadvantages, it is desirable to create an initiating event list using a variety of methods, and it is important to avoid missing initiating events. From this perspective, it is expected that a logical evaluation method such as an HBFT (Heat Balance Fault Tree) will reduce potential errors in the initiating event selection, allow the selection of negligible initiating events, and contribute to systematic initiating event selection of SMART. As the design changes continue to improve the safety of SMART, the selected initiating events may change. After the design change of SMART, the design change should be reflected and the initiating event screening should be performed again. At the time of screening the initiating events of SMART, it is expected that the initiating events of SMART will be systematically selected using the empirical evaluation method and the logical evaluation method discussed in this paper.

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