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Development of a systematic sequence tree model for feed-and-bleed operation under a combined accident

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ABSTRACT

Combined accidents are considered as very rare events and therefore are not usually considered in deterministic or probabilistic safety analyses. Yet, despite being rare, it is necessary to examine combined accidents as their effects could become very large following poor treatment from a lack of information. In a combined accident, the most important safety actions are the functions for heat removal, as initiating and maintaining proper safety actions are critical to prevent core damage. In order to analyze the plant conditions requiring safety action to prevent core damage and the success conditions of the safety actions under a combined accident, sequence tree modeling is suggested. A sequence tree is a branch model to classify the plant condition considering plant dynamics. Since a sequence tree model can reflect the plant dynamics arising from the interaction of different accident timings and plant conditions, and also from the relations between operator action, mitigation systems, and the indicators for operation, it can be used to develop a dynamic event tree model. To develop the sequence tree model, indicators are identified which inform about the availability of heat removal mechanisms and the plant condition. This study develops a sequence tree model to core damage requiring F&B operation under a combined accident, designated here as the combination of a total loss of feedwater accident with a loss of coolant accident. Sequences of the sequence tree model can be categorized according to second accident timing. With a sampling analysis, the practical accident cases are obtained. The sequence tree model can translate into a dynamic event tree model if the initiating event frequency under a combined accident can be quantified.

1. Introduction

The 2011 Fukushima accident in Japan revealed that even a very rare event must be considered in order to prevent radioactive release to the environment from poor treatment based on a lack of information (Kim, 2014). A combined accident, defined as two initiating events occurring at the same or different times, is one of these very rare events and thus is not considered in current safety analyses.

In a combined accident, the accident sequence is very complicated and it is therefore not easy to identify and perform the proper actions. In order to decide the proper operator actions, it is necessary to identify the sequences to core damage when specific operations fail. With the development of a systematic model to analyze combined accidents, designers can understand accident sequences in detail and operators can perform the proper safety actions.

This study addresses this issue by suggesting a sequence tree model to systematically analyze accident sequences. A sequence tree is a type of branch model that categorizes the plant condition by considering plant dynamics. Using the sequence tree model, all possible scenarios requiring a specific safety action to prevent core damage can be identified, and success conditions of the safety actions performed during a complicated situation, such as a combined accident, will be also identified. As the sequence tree model can reflect the plant dynamics that arise from the interaction of different accident timings with the plant condition, and also from the interactions between operator action, mitigation systems, and the indicators for operation, the model can be used to develop a dynamic event tree model (Hsueh and Mosleh, 1996; Karanki et al., 2015; SNL, 2012).

There are various dynamic probabilistic safety assessment (PSA) models to analyze plant dynamics and to quantify the frequencies

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of sequences (Siu, 1994; Swaminathan and Smidts, 1999). Siu (1994) summarized the alternative methodologies for dynamic system analysis, including extensions of the event tree/fault tree methodology, as well as explicit and implicit state transition methods. Swaminathan and Smidts (1999) developed an event sequence diagram (ESD) framework to capture most of the complex dynamic phenomena. These dynamic PSA models for single events include a considerable amount of information, including time. The plant dynamics under combined accidents however are not as easy to understand, resulting in numerous factors to treat in a dynamic PSA model for combined accidents. A sequence tree model is developed here to analyze all possible core damage sequences due to the failure of target safety functions under a combined accident. The sequence tree model focuses on the change points of plant condition, and will be useful for operators and system designers to understand the various plant conditions under a combined accident. ESDs can also be applied to analyze combined accidents. But sequence tree models will provide more visual appeal to appreciate the accident dynamics compared to ESDs (Swaminathan and Smidts, 1999).

There is a lack of research related to calculating event probabilities for combined accidents, such as initiating event frequency and timing distribution of the second accident. If these probabilities can be estimated, the core damage frequency of combined accidents can be calculated along with the success criteria for each sequence in the sequence tree model based on Karanki's study with sampling analysis. Karanki's approach of dynamic event tree quantification of risk avoids the need to specify a priori the sequence of stochastic events prior to the plant response simulation considering the support system dependencies and operator action timing distribution (Karanki and Dang, 2016).

The target safety action for this study is a feed-and-bleed (F&B) operation. F&B operation directly cools down the reactor coolant system (RCS) using the primary cooling system when residual heat removal by the secondary cooling system is not available (Iannello, 1984; Kim et al., 2014). F&B operation is critical as it is the last resort for heat removal to prevent core damage. Related systems include the safety depressurization system (SDS) and the safety injection system (SIS). The SDS provides a manual means of rapidly depressurizing the RCS for the highly unlikely event of a total loss of feedwater (TLOFW). The reduced RCS pressure allows the high pressure safety injection (HPSI) flow to replenish and eventually exceed the mass flow rate out through the SDS prior to core uncovery (KHNP, 2001).

It is difficult for operators to recognize the necessity of F&B operation in the case of a combined accident that includes a failure of the secondary cooling system. Operators may spend a considerable amount of time arriving at the entry of a proper emergency operating procedure (EOP) that contains F&B operation, as it is a functional recovery procedure much less familiar than optimal recovery procedures.

Previous studies have focused on accidents involving a TLOFW accident to demonstrate the use of F&B operation (Kwon et al., 1995; Kwon and Song, 1996; Pochard et al., 2002; Reventós et al., 2007; Sherry et al., 2013). However, little research has focused on combined accidents requiring F&B operation. In one such study, Kim et al. (2014) indicated that plant conditions requiring F&B operation should not be limited to single events such as a TLOFW accident but also include combined accidents. The plant conditions necessitating F&B operation can be categorized as transients with loss of feedwater and a loss of coolant accident (LOCA), and transients with loss of feedwater. Although transients with loss of feedwater and LOCA are very rare, the resulting highly complicated plant condition makes it difficult for operators to identify the necessity of F&B operation. Yet not every plant condition characterized by transients with loss of feedwater and LOCA require F&B operation; if sufficient coolant is injected by the SIS, F&B operation would not be necessary. However, if the break size is too small to sufficiently decrease RCS pressure, the SIS cannot inject coolant and so the operator should initiate F&B operation. Thus, a sequence tree model for F&B operation under a combined accident can be developed.

This paper is organized as follows. Section 2 includes an identification of the indicators which identify the availability of heat removal mechanisms and the plant condition. Section 3 explains the development process for a sequence tree model considering a TLOFW accident and a TLOFW accident with LOCA. Section 4 gives a sampling analysis using MARS code and MOSAIQUE to identify realistic cases, with discussion and conclusions found in Section 5.

2. Indicators related to heat removal mechanisms and plant condition

Available and sufficient heat removal mechanisms are the most important factors to cool down the RCS, as insufficient heat removal mechanisms inevitably lead to core damage (Corcoran et al., 1981). Although combined accident scenarios are complicated, from the viewpoint of heat removal, the sequences to core damage without safety action can be easily identified. Therefore, it is necessary to identify the indicators which recognize the availability of the heat removal mechanisms, as well as plant conditions that are affected by the heat source and heat removal mechanisms.

According to accident type and safety function availability, the available heat removal mechanisms can be determined as shown in Table 1.

All success sequences are cooled down by single or multiple heat removal mechanisms: secondary side (SS), F&B transient, F&B operation, SS and F&B transient, and F&B transient and F&B operation. Fig. 1 shows all possible sequences from the viewpoint of heat removal mechanism availability. Sequences to core damage are shown in red.

Available and sufficient heat removal mechanisms strongly affect core damage. Therefore, indicators (sequence change points) which identify the availability of the heat removal mechanisms should be considered in accident sequences. A flow chart is developed to identify available heat removal mechanisms according to accident sequence (Figs. 2a and 2b), which can categorize all possible scenarios in consideration of heat removal mechanism availability. The flow chart is developed based on EOP and PSA models (KHNP, 2001).

Table 1
Type of heat removal mechanisms in pressurized water reactors.

Heat removal mechanism		Necessary safety functions/plant condition	Indicator
Indirect cooling by secondary side		Available secondary side system	Steam generator (SG) level
		Natural or forced circulation in primary side	RCS inventory
Direct cooling at primary side	Break and SIS (F&B transient)	Available SIS	Safety injection actuation signal (SIAS), availability of SIS
		RCS pressure	Pressurizer (PZR) pressure
	SDS and SIS (F&B operation)	Available SIS and SDS	Availability of SIS and SDS
		Initiation by operators	Entry conditions of F&B operation
		RCS pressure	PZR pressure