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# Development of a feed-and-bleed operation strategy with hybrid-SIT under low pressure condition of PWR

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## HIGHLIGHTS

- The novel F&B operation strategy with H-SIT and LPSI is developed.
- The effectiveness of the H-SITs is verified using thermo-hydraulic simulations.
- Success criteria considered for the new F&B operation strategy is identified.
- A PSA model of APR+ reflecting the new F&B strategy with H-SIT is developed.
- A risk analysis of the proposed F&B operation strategy is performed.

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## ABSTRACT

While safety functions in current nuclear power plants are mainly provided by active safety systems, recently passive safety systems are being combined with the active systems to strengthen accident mitigation capability and therefore enhance overall plant safety. To this end, securing long-term cooling of the core is of particular importance. This study considers the hybrid safety injection tank (H-SIT), a passive injection system, as a target component to develop a long-term cooling strategy using active and passive systems concurrently.

In the feed-and-bleed (F&B) operation, one of the important long-term cooling strategies to maintain core safety in pressurized water reactors, low pressure safety injection (LPSI) pumps are typically considered inoperable as depressurization is first required, which leads to core dry-out before reaching LPSI operable pressure. This study investigates whether H-SITs, with the important design feature of passive coolant injection under any pressure condition of the primary coolant system, can make up the core during depressurization thereby allowing LPSI pumps to be used in F&B operation as an additional means of long-term cooling. The effectiveness of the H-SITs is verified using thermal-hydraulic simulations, and based on the results a novel F&B operation strategy with H-SITs and LPSI pumps is developed. A probabilistic safety assessment (PSA) model is then developed in order to assess the risk effect of the suggested strategy. PSA results demonstrate that the proposed strategy lowers core damage frequency in the target plant by 5.0 percent in the case of a small break loss of coolant accident. Total core damage frequency of the plant decreases by 4.8 percent compared to the reference model, and also lowers the number of cutsets by around 13 percent from the original value.



*Abbreviations:* APR+, (advanced power reactor plus); CCF, (common cause failure); CDF, (core damage frequency); CET, (core exit temperature); CSP, (containment spray pump); EOP, (emergency operating procedure); F&B, (feed and bleed); HEP, (human error probability); H-SIT, (hybrid safety injection tank); LOCA, (loss of coolant accident); LPSI, (low pressure safety injection); MARS, (multi-dimensional analysis of reactor safety); NPP, (nuclear power plant); PAFS, (passive auxiliary feedwater system); POSRV, (pilot operated safety relief valve); PSA, (probabilistic safety assessment); PWR, (pressurized water reactor); RCGVS, (reactor coolant gas venting system); RCGVV, (reactor coolant gas venting valve); RCS, (reactor coolant system); SAMG, (severe accident management guideline); SBO, (station black out); SCP, (shutdown cooling pump); SCS, (shutdown cooling system); SIP, (safety injection pump).

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## 1. Introduction

Most critical safety functions in current nuclear power plants (NPPs) are provided by numerous active safety systems. Yet in order to meet future safety goals, relying on these active systems alone does not seem to be viable. As passive systems effectively mitigate station black out (SBO) accidents (Kumar et al., 2013) and also contribute diversity to other accident mitigation measures, the combination of passive and active systems has become paramount in the nuclear industry to enhance plant safety (Juhn et al., 2000; John and Devine, 1996).

Recent research on the development of passive systems, such as a passive auxiliary feed-water system (PAFS), has been carried out in numerous cases to enhance NPP safety (Chang et al., 2013; Cho et al., 2012; Byun et al., 2000). Nevertheless, general passive systems have a critical limitation, especially for passive injection systems. As these systems use gravity as their driving force (Buchner and Fabian, 1994), it is difficult to inject coolant into the reactor coolant system (RCS) under high pressure, thus requiring depressurization. RCS depressurization, however, inevitably causes the loss of core inventory and is therefore not recommended to secure plant safety.

As a countermeasure, the hybrid safety injection tank (H-SIT) system was invented to passively inject coolant into the RCS under any pressure condition without depressurization (Kwon and Park, 2013). While this system is initially planned to be integrated into the APR+ (advanced power reactor plus) in Korea, it can be available for any pressurized water reactor (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. Four H-SITs are planned to be installed in the target plant, each with a 6.35 cm (2.5 in) diameter equalizing pipe and manual operation. The diameter and height of the tanks are 2.743 m and 12.84 m, respectively, with internal volume and pressure of 68.1 m$^3$ and 40 bar, respectively. Its design temperature and pressure are 370 °C and 17.0 MPa. Operation of the equalizing valve in the H-SIT system is controlled manually. Experimental and theoretical verification of the H-SIT system has been completed by the Korea Atomic Energy Research Institute (KAERI) (Ryu et al., 2016). Fig. 1 shows the conceptual layout of the H-SIT system.

Long-term cooling of the core is the ultimate goal of all accident mitigation actions for nuclear safety. In the conventional PWR emergency operating procedure (EOP), there are three long-term cooling strategies: operation of the shutdown cooling system (SCS) or residual heat removal system, maintaining the secondary cooling system, and feed-and-bleed (F&B) operation (KHNP, 2015). These strategies require the operation of long-term cooling components, such as high-pressure safety injection (HPSI) pumps, reactor heat removal pumps, and the auxiliary feed water system (US NRC, 1975; Kwon and Song, 1996). The soundness of these components and systems is critical as long-term mitigation strategies cannot succeed if they are not fully functional during an accident. In case of the H-SIT system, even though it can be used as a high-pressure injection pump in an accident, under its original design it cannot be used for long-term cooling on account of limited coolant inventory. Previous research related to H-SIT operation has mainly focused on the development of mitigation strategies for SBO or other severe accidents in which the active safety systems fail; in accidents where electricity is available (Jeon and Kang, 2015; Jeon et al., 2016), the active systems are preferentially employed

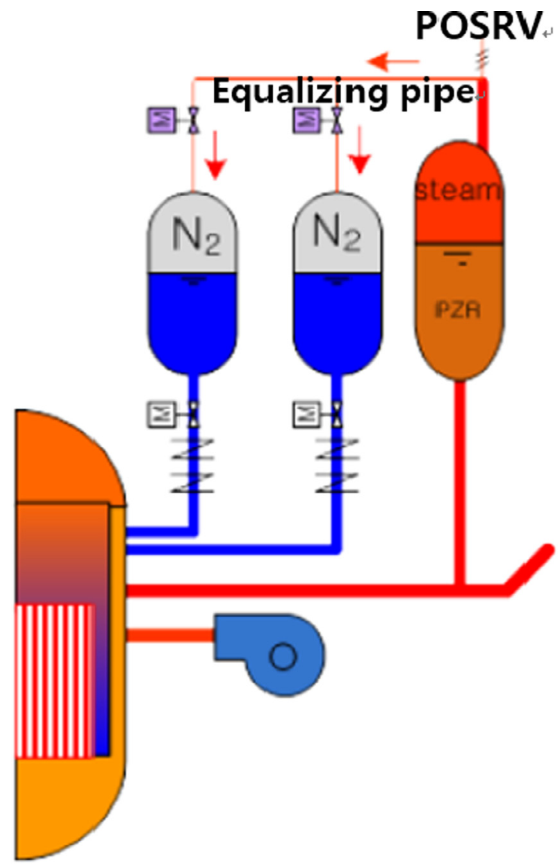


**Fig. 1.** Conceptual layout of an H-SIT system.

because passive systems have less operational flexibility on account of their lower driving force (Fil et al., 1999). Therefore, the purpose of H-SIT operation is to extend core failure time in order to secure more available time for the recovery of the safety components or electricity, not for long-term cooling.

Despite this, the H-SIT system can be a good supplemental or "assistant" component as its passive injection can be used under any pressure condition. Even though some long-term cooling components may be functionally available in certain accident cases, they cannot be used if their operating conditions are unsatisfied. Temporary injection by the H-SITs can serve in these situations until the entry condition of other long-term cooling components is met. Thus, if the H-SIT system is operated in conjunction with other long-term cooling components, the conditions previously regarded as core failure can be changed to core safety with long-term cooling.

This study focuses accordingly on the development of an accident mitigation strategy utilizing H-SITs to achieve long-term cooling in order to secure a larger variety of safety actions and enhance plant safety. MARS ver. 1.3 is used as a thermal-hydraulic code. MARS was developed by integrating the one-dimensional RELAP/MOD3 with the multi-dimensional COBRA-TF code (Jeong et al., 1999), and the code inputs of the APR+ and H-SIT were provided by Korea Hydro & Nuclear Power Co., Ltd. (KHNP).

This work is organized as follows. In Section 2, a F&B operation strategy with H-SITs is developed for a low pressure condition. In Section 3, a reference probabilistic safety assessment (PSA) model of the APR+ is first developed using the AIMS program to compare the original APR+ PSA model with a revised one reflecting the new long-term cooling strategy with H-SITs. Then, a risk analysis of the proposed F&B operation strategy is performed based on the reference PSA model. Concluding remarks are presented in Section 4.