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Variability of plant risk due to variable operator allowable time for aggressive cooldown initiation

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ABSTRACT

Recent analysis results with realistic assumptions provide the variability of operator allowable time for the initiation of aggressive cooldown under small break loss of coolant accident or steam generator tube rupture with total failure of high pressure safety injection. We investigated how plant risk may vary depending on the variability of operators' failure probability of timely initiation of aggressive cooldown. Using a probabilistic safety assessment model of a nuclear power plant, we showed that plant risks had a linear relation with the failure probability of aggressive cooldown and could be reduced by up to 10% as aggressive cooldown is more reliably performed. For individual accident management, we found that core damage potential could be gradually reduced by up to 40.49% and 63.84% after a small break loss of coolant accident or a steam generator tube rupture, respectively. Based on the importance of timely initiation of aggressive cooldown by main control room operators within the success criteria, implications for improvement of emergency operating procedures are discussed. We recommend conducting further detailed analyses of aggressive cooldown, commensurate with its importance in reducing risks in nuclear power plants.

1. Introduction

The safety of a nuclear power plant (NPP) can be enhanced by increasing preparedness for various types of accidents. By properly incorporating insights into methods of risk reduction, preparedness for such accidents can be efficiently enhanced with limited resources and time constraints. Probabilistic safety assessment (PSA) serves as a tool for systemically analyzing the safety of an NPP, taking a macroscopic view incorporating potential initiating events, scenarios, and their consequences.

The accident sequence we focused on was a small break loss of coolant accident (SBLOCA) or a steam generator tube rupture (SGTR) followed by failure of high-pressure safety injection (HPSI) in a pressurized water reactor (PWR). In this situation, the pressure of the reactor coolant system (RCS) does not decrease fast enough for injection to the RCS by the safety injection tank (SIT) or for low-pressure safety injection (LPSI) to be initiated. Meanwhile, the RCS gradually loses inventory due to the break flow, which potentially leads to uncovering the reactor core. In many PSA studies, e.g., Surry [1], Sequoyah [2], and Zion [3], core damage was assumed in such a situation.

However, thermal-hydraulic (TH) experiments [4–6] and code analyses [7–11] have shown that this situation can be mitigated by rapidly cooling down and depressurizing the RCS to the pressure at which SIT injection begins. Such an action by the main control room (MCR) operators is described in many ways, including aggressive cooldown, secondary-side depressurization, rapid cooldown, etc. Here, we refer to this action as aggressive cooldown. Relatively short available time (about 15 min) for MCR operators to initiate aggressive cooldown resulted in high human error probability (HEP) that was sometimes conservatively assumed to be 1, i.e. aggressive cooldown is conservatively assumed to fail always.

However, recent TH code analyses show that the risk of SBLOCA or SGTR with total failure of HPSI may be variable depending on the break size. Cho et al. [12] found that the decay heat could be successfully removed with only normal secondary cooling in loss of coolant accidents (LOCAs) with break sizes below 1.4 inches. Fynan et al. [13] developed a success criteria map for aggressive cooldown as a function of break size and operator action time which allow more available time for operators as break size decreases. Han and Yang [14] and Kim et al. [15] also performed TH code analysis and

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argued that SGTR with total failure of HPSI may not results in core damage in 24 h without operator intervention.

In the literature, it is often mentioned that SBLOCA or SGTR combined with HPSI failure is an important accident sequence and therefore, aggressive cooldown is an important accident mitigation action. With quantitative analysis of the importance of aggressive cooldown based on a PSA of an NPP, the purpose of this study is to provide how the plant risk may vary depending on the variability of the risks due to SBLOCA or SGTR with total failure of HPSI. In Section 2, theoretical considerations on the variability of plant risk are described. In Section 3, the importance of aggressive cooldown is analyzed not only from the viewpoint of overall plant risk, but also from the viewpoint of risks due to specific initiating events (IEs). In Section 4, implications of the importance of aggressive cooldown for emergency operating procedures (EOPs) are discussed. Section 5 provides the conclusions of this paper.

2. Theoretical considerations

2.1. Core damage frequency

The variability of plant risk can be demonstrated by illustrating the sensitivity of the core damage frequency (CDF) to the failure probability of aggressive cooldown. The CDF of an NPP can be represented as:

$$CDF = \sum_h \sum_i f_{IE_h} \cdot Pr(IE_h \rightarrow CDS_{h,i}) \tag{1}$$

where

CDF: core damage frequency
IE_h: initiating event h
f_{IE_h}: frequency of initiating event h
$Pr(IE_h \rightarrow CDS_i)$: conditional probability that the occurrence of IE_h leads to $CDS_{h,i}$
$CDS_{h,i}$: core damage sequence i given the occurrence of initiating event h

Because aggressive cooldown is related with two initiating events, SBLOCA and SGTR, Equation (1) can be rewritten as:

$$\begin{aligned} CDF = & f_{SBLOCA} \sum_i Pr(SBLOCA \rightarrow CDS_{SBLOCA,i}) \\ & + f_{SGTR} \sum_i Pr(SGTR \rightarrow CDS_{SGTR,i}) \\ & + \sum_{\substack{h \\ IE_h \neq SBLOCA \\ IE_h \neq SGTR}} \sum_i f_{IE_h} \cdot Pr(IE_h \rightarrow CDS_{h,i}) \end{aligned} \tag{2}$$

The core damage sequences of SBLOCA and SGTR can be divided into those that include the failure of aggressive cooldown and those that do not. Therefore, the CDF can be rewritten as:

$$\begin{aligned} CDF = & f_{SBLOCA} \{ a_{SBLOCA} \cdot \Pr(X_{ASC} \\ & = Fail) + b_{SBLOCA} \} + f_{SGTR} \{ a_{SGTR} \cdot \Pr(X_{ASC} \\ & = Fail) + b_{SGTR} \} + \sum_{\substack{h \\ IE_h \neq SBLOC \\ IE_h \neq SGTR}} \sum_i f_{IE_h} Pr(IE_h \rightarrow CDS_{h,i}) \end{aligned} \tag{3}$$

where

X_{ASC}: random variable for aggressive cooldown
a_{SBLOCA}: the sum of all cutsets that include the failure of aggressive cooldown given the occurrence of SBLOCA
b_{SBLOCA}: the sum of all cutsets that do not include the failure of aggressive cooldown given the occurrence of SBLOCA
a_{SGTR}: the sum of all cutsets that include the failure of aggressive cooldown given the occurrence of SGTR
b_{SBLOCA}: the sum of all cutsets that do not include the failure of aggressive cooldown given the occurrence of SGTR

By defining the following two factors a and b,

$$a = a_{SBLOCA} \cdot f_{SBLOCA} + a_{SGTR} \cdot f_{SGTR} \tag{4}$$

$$\begin{aligned} b = & b_{SBLOCA} \cdot f_{SBLOCA} + b_{SGTR} \cdot f_{SGTR} \\ & + \sum_{\substack{h \\ IE_h \neq SBLOCA \\ IE_h \neq SGTR}} \sum_i f(IE_h) CCDP(IE_h \rightarrow CDS_i) \end{aligned} \tag{5}$$

The CDF can be now rewritten as:

$$CDF = a \cdot \Pr(X_{ASC} = Fail) + b \tag{6}$$

It can be seen that the CDF is linearly related with the failure probability of aggressive cooldown. The slope of the linear relation is determined by the frequencies of SBLOCA and SGTR, weighted by two factors a_{SBLOCA} and a_{SGTR}, respectively. The y-intercept of the linear relation is determined by the frequencies of SBLOCA and SGTR, weighted by two factors b_{SBLOCA} and b_{SGTR}, respectively, and the CDFs caused by those IEs other than SBLOCA and SGTR.

The linear relationship described above mainly results from application of the rare event approximation in calculating the CDF for the plant from the identified minimal cutsets (MCSs). More details on the linear relationship between a measure of risk and basic event probability are provided in Wall and Worledge [16].

2.2. Conditional core damage probability

Because aggressive cooldown is a mitigation strategy that applies only when an SBLOCA or SGTR occurs, aggressive cooldown is particularly important when the analysis is focused on SBLOCA and SGTR situations. The conditional core damage probability (CCDP) [17] for an IE describes the likelihood of core damage after occurrence of a specific IE.

The CCDPs of an SBLOCA and an SGTR can be defined and given as follows:

$$\begin{aligned} CCDP_{SBLOCA} = & \sum_i Pr(SBLOCA \rightarrow CDS_{SBLOCA,i}) = a_{SBLOCA} \cdot \Pr(X_{ASC} \\ & = Fail) + b_{SBLOCA} \end{aligned} \tag{7}$$

$$\begin{aligned} CCDP_{SGTR} = & \sum_i Pr(SGTR \rightarrow CDS_{SGTR,i}) = a_{SGTR} \cdot \Pr(X_{ASC} \\ & = Fail) + b_{SGTR} \end{aligned} \tag{8}$$

It can be seen that the CCDPs of SBLOCA and SGTR have linear relations with the failure probability of aggressive cooldown. The slopes of the linear relations (a_{SBLOCA} and a_{SGTR}) are the failure probability of HPSI and therefore they are essentially same with each other. This is because SBLOCA or SGTR combined with the failure of HPSI and the failure of aggressive cooldown is modeled to result in core damage. The y-intercepts of the linear relations (b_{SBLOCA} and b_{SGTR}) are related to the failures of other parts such as

LPSI and the parts common to both HPSI and LPSI. The different characteristics and mitigation strategies for an SBLOCA and SGTR are also related to the difference in y-intercepts.

2.3. Importance measures

Importance measures are used to provide importance rankings of components, maintenance activities, or human operation. An overview of importance measures used in PSA is provided in van der Borst and Schoonakker [18]. Some of the most widely used importance measures [19,20] are Fussel-Vesely importance, risk reduction worth (RRW), and risk achievement worth (RAW).

The importance of aggressive cooldown can be quantitatively measured with importance measures. Fussel-Vesely importance, RRW, and RAW of aggressive cooldown are given as:

$$FV_{ASC} = \frac{a \cdot \Pr(X_{ASC} = Fail)}{a \cdot \Pr(X_{ASC} = Fail) + b} \tag{9}$$

$$RRW_{ASC} = \frac{a \cdot \Pr(X_{ASC} = Fail) + b}{b} = \frac{a}{b} \cdot \Pr(X_{ASC} = Fail) + 1 = \frac{1}{1 - FV_{ASC}} \tag{10}$$

$$RAW_{ASC} = \frac{a + b}{a \cdot \Pr(X_{ASC} = Fail) + b} = \left(\frac{1}{\Pr(X_{ASC} = Fail)} - 1\right) \cdot FV_{ASC} + 1 \tag{11}$$

From Equations (9)-(11), it should be noted that RRW and RAW can be calculated based on the failure probability of the aggressive cooldown and Fussel-Vesely importance.

3. Application to a nuclear power plant

3.1. Overall plant risk viewpoint

The importance of aggressive cooldown was analyzed using the PSA model for the Hanul nuclear (HUN) Units 3 and 4, the PRiME 2.1 HUN 3&4 model [21]. The event trees and fault trees were constructed and the one-top fault tree was generated using AIMS-PSA (Advanced Information Management System for PSA) [22]. The generated one-top fault tree was solved using FTREX (Fault Tree Reliability Evaluation eXpert) [23]. Using a cutoff value of 1×10^{-11}, MCSs were generated and the CDF was determined with the rare event approximation.

The success criteria for aggressive cooldown given in the Individual Plant Examination for Palo Verde Units 1, 2, and 3 (the reference plants for HUN Units 3 and 4) [24] are:

- Operator action to start an aggressive cooldown is initiated within 15 min of a SBLOCA or SGTR.
- Auxiliary feedwater is supplied to both steam generators (SGs).
- Steam is removed from both SGs using one of the two atmospheric dump valves (ADVs) on each SG or two of the eight turbine bypass valves.
- LPSI flow is delivered from the refueling water tank (RWT) using one of two LPSI pumps through at least one LPSI injection line.
- At least two of the four SITs supply water to the RCS during the cooldown to keep the core covered during depressurization.

To help readers understand the time urgency of operators' aggressive cooldown initiation during SBLOCA with HPSI failure, TH analysis is performed with a best-estimate code MARS [25,26] (more specifically MARS-KS v1.4). For HUN Units 3 and 4 model [27], the situation of SBLOCA (2 inch in diameter) followed by HPSI failure is analyzed for five cases of operators' action time: operators' ADVs opening at 600, 1200, 1800, 2400 s after reactor trip and no action. Figs. 1–3 show RCS pressure, reactor core level, and peak cladding temperature for the five cases. It is assumed that RCS cooldown and depressurization by opening ADVs is performed while satisfying the limit in RCS cooldown rate (56 °C/hr) for preventing pressurized thermal shock (PTS).

Without operators' action, RCS pressure remained above SIT injection pressure while gradually losing RCS inventory until the core is uncovered and eventually damaged. Fig. 2 shows that the core level was recovered and hence core damage could be prevented when operators started aggressive cooldown by opening ADVs 600, 1200, and 1800 s after reactor trip. When ADVs were opened 2,400 s after reactor trip, peak cladding temperature exceeded the safety limit (1204 °C) as shown in Fig. 3.

The HEP of aggressive cooldown is estimated with consideration of diagnosis within allowed diagnosis time by MCR operators, errors of omission in using written procedures, performance shaping factors, and recovery factors. Due to the relatively short allowed operator action time in the success criteria [28,29] and other performance shaping factors such as procedures and training, the probability that the MCR operators fail to initiate aggressive cooldown within the success criteria was estimated to be 0.59 in the PRiME 2.1 HUN 3&4 model, which accounts for >98% of the total failure probability of aggressive cooldown. Even though the allowed operator action time of SGTR is, in general, longer than that of SLOCA, the former is conservatively assumed to be same with the latter. Because of this dominance of the operator action failure probability, failure of MCR operators to initiate aggressive cooldown within the success criteria is nearly synonymous with failure of aggressive cooldown. Failure of MCR operators to rapidly perform aggressive cooldown occurred in 4 of the 20 highest risk MCSs.

Fig. 4 shows how CDF changes as the failure probability of aggressive cooldown changes. The base case is a failure probability of aggressive cooldown of 0.59. As explained in Section 2, the CDF has a linear relation with the failure probability of aggressive cooldown.

The Fussel-Vesely importance of failure of aggressive cooldown was calculated to be 0.099745, the 11th highest position in the Fussel-Vesely importance ranking. Based on the failure probability of aggressive cooldown and Fussel-Vesely importance, RRW and RAW for aggressive cooldown are calculated as:

$$RRW_{ASC} = \frac{1}{1 - FV_{ASC}} = 1.111 \tag{12}$$

$$RAW_{ASC} = \left(\frac{1}{\Pr(X_{ASC} = Fail)} - 1\right) \cdot FV_{ASC} + 1 = 1.069 \tag{13}$$

The RRW was calculated to be 1.111. It indicates that the plant risk may decrease by about 10% if aggressive cooldown can always be performed successfully, i.e., if the failure probability of aggressive cooldown is assumed to be 0. The RAW is calculated to be 1.069. It indicates that plant risk will increase by 6.9% if aggressive cooldown can never be performed, i.e., if the failure probability of aggressive cooldown is assumed to be 1. It is worth noting that aggressive cooldown was not credited in the PSA studies of Surry 0, Sequoyah [1], Zion [3], or many others. In other words, the CDF may decrease by up to 10% if aggressive cooldown is reliably performed, while the CDF may increase by up to 6.9% if aggressive cooldown is very difficult to perform.

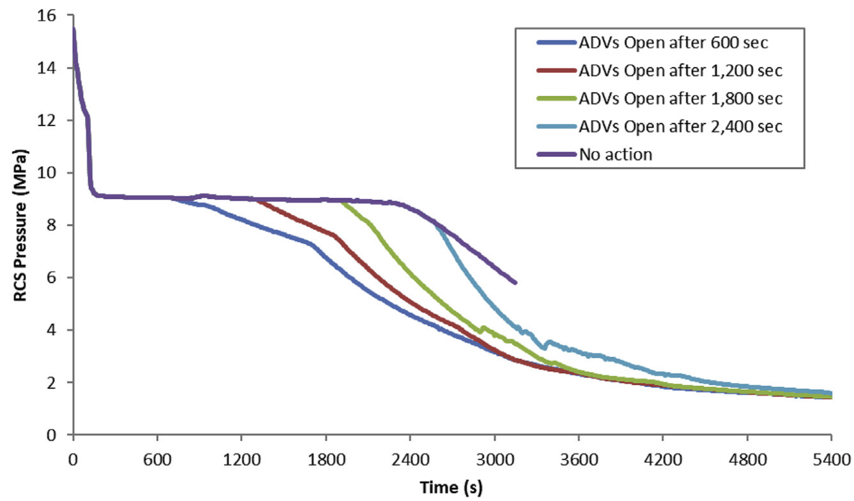

Fig. 1. RCS pressure by opening ADVs at different time points.

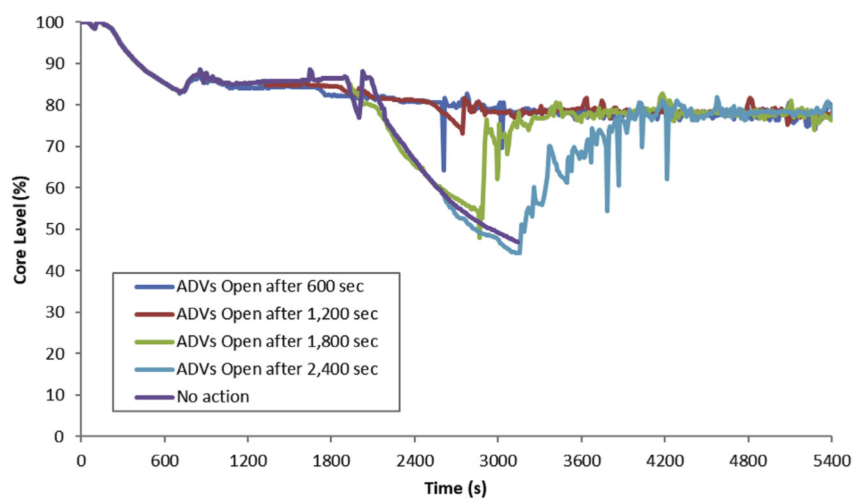

Fig. 2. Core level by opening ADVs at different time points.

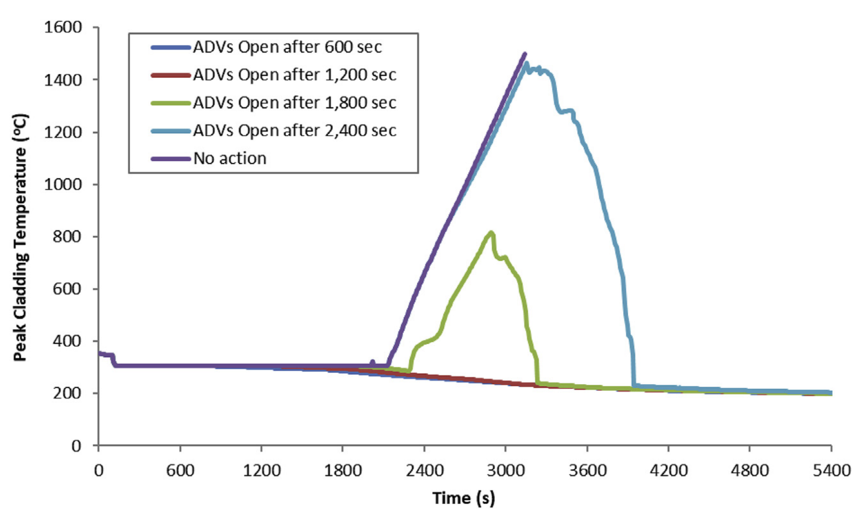

Fig. 3. Peak cladding temperature by opening ADVs at different time points.

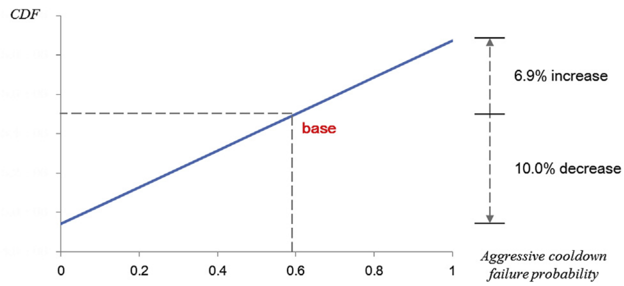

Fig. 4. Sensitivity of the CDF to the probability of failure of aggressive cooldown.

3.2. Individual accident management viewpoint

Table 1 and Table 2 show the three scenarios with the greatest core damage potential after an SBLOCA or SGTR, respectively, with the CCDP percentages for each and the sum of the three CCDP percentages. The total CCDP percentages in Tables 1 and 2 represent the portions of the likelihood of core damage after the occurrence of an SBLOCA or SGTR, respectively.

Total failure of HPSI combined with failure of aggressive cooldown was found to be the most significant potential core damage scenario after an SBLOCA or SGTR. It represented 40.49% and 63.84% of the total CCDPs of an SBLOCA and SGTR, respectively. Therefore, if this specific core damage scenario can be eliminated, the potential for core damage could be significantly reduced (up to 40.49% and 63.84%) after an SBLOCA or SGTR.

The three scenarios with the greatest core damage potential after an SBLOCA or SGTR comprise about 75% of the total CCDPs for the two IEs. The ranks based on the CCDPs for an IE provide priorities for further improving preparedness for the IE. For example, any measures aimed at preventing the potential core damage scenarios shown in Tables 1 and 2 may significantly reduce up to 75% of core damage potential after an SBLOCA or SGTR.

The sensitivity of the total CCDPs for an SBLOCA and SGTR with respect to the failure probability of aggressive cooldown was analyzed (Fig. 5). The failure probability of aggressive cooldown was assumed to be 0.59, the base case for the sensitivity analysis. Consistent with Tables 1 and 2, the total CCDPs may decrease by up to 40.49% for an SBLOCA and 63.84% for an SGTR if aggressive cooldown can be performed highly reliably. Conversely, the CCDPs may increase by 28.51% for an SBLOCA and 44.49% for an SGTR if it is assumed that aggressive cooldown can never be performed successfully. The linear relations of the total CCDPs for an SBLOCA and SGTR to the failure probability of aggressive cooldown indicate how significant aggressive cooldown is as a mitigation action under these situations.

As discussed in Section 3.1, failure of the MCR operators to initiate aggressive cooldown within the success criteria is the most important and dominant cause of failure of aggressive cooldown. Therefore, any measures that enhance the performance of the MCR operators after an SBLOCA or SGTR will be very important in increasing preparedness for such an event. Those measures include improvement in EOPs and training of MCR operators with specific focus on aggressive cooldown. Section 4 discusses the implications of the importance of aggressive cooldown in reducing risk for the EOPs for a SBLOCA and SGTR.

3.3. Discussion

We found that the total CCDP for an SGTR was 36% lower than that for an SBLOCA. Under an SBLOCA situation, recirculation must be successfully performed after LPSI. Under an SGTR situation, it is important for the MCR operators to properly maintain RCS pressure and HPSI flow so that the RCS pressure and SG pressure are equally maintained to minimize the break flow through the ruptured tube. This difference in mitigation strategies for SBLOCA and SGTR contributes to the difference in the total CCDPs.

The slopes of the lines for an SBLOCA and SGTR are nearly the same, while the y-intercepts are different (Fig. 5). The slopes are related to failures in the HPSI (Fig. 6), which includes two HPSI pumps and associated valves dedicated to the HPSI lines, while the y-intercepts are related to failures in other parts such as the LPSI and parts common to both the HPSI and LPSI (Fig. 6). The different characteristics and mitigation strategies for an SBLOCA and SGTR are also related to the difference in y-intercepts.

Because failures in the HPSI are common to both an SBLOCA and SGTR, the slopes of two lines are nearly the same (Fig. 5), as mentioned in Section 2. Failures in recirculation due to plugging of the containment sump and common cause failure of the containment sump isolation check valves were found to be the main factors contributing to the difference in the y-intercepts (Fig. 5).

4. Implications for emergency operating procedures

4.1. General implications

The CCDP percentages for an IE and their rankings provide important information on priorities for improvements required to better manage that IE (Tables 1 and 2). Each CCDP percentage corresponds to a potential core damage scenario after an IE. Core damage scenarios with the highest CCDP rankings warrant greater attention.

After a reactor trip followed by an IE such as an SBLOCA or SGTR, MCR operators must manage the accident situation according to EOPs. EOPs play a decisive role in the performance of MCR operators under emergency situations. For MCR operators to exhibit high performance in an emergency, it is important to clearly identify necessary mitigation actions and specify them in the EOPs along with their success criteria. It is also important for EOPs to properly identify the importance of each mitigation action so that mitigation actions with high importance or high urgency can be given highest priority. Insight into relative risks provided by this study can contribute to improving EOPs so that the overall risk is minimized.

4.2. Implications specific to aggressive cooldown

The most significant potential core damage scenario after occurrence of an SBLOCA or SGTR was found to be failure of HPSI followed by failure of aggressive cooldown (Tables 1 and 2). The core damage potential is highly sensitive to the failure probability

Table 1
The three scenarios with the greatest core damage potential after an SBLOCA.

Rank	Scenario	CCDP Percentage
1	Total failure of HPSI combined with failure of aggressive cooldown	40.49%
2	Containment sump failure due to plugging	28.32%
3	Common cause failure of containment sump isolation check valve	6.41%

Table 2
The three scenarios with the greatest core damage potential after an SGTR.

Rank	Scenario	CCDP Percentage
1	Total failure of HPSI combined with failure of aggressive cooldown	63.84%
2	Operator fails to control RCS pressure and HPSI flow combined with other human errors	8.64%
3	Common cause failure of RWT discharge isolation check valves	5.13%

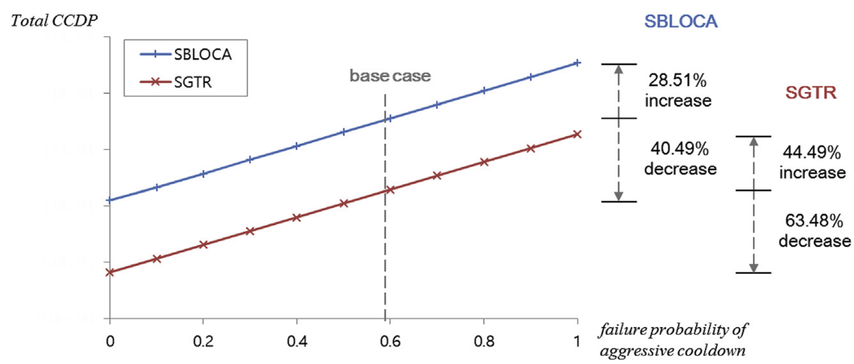

Fig. 5. Sensitivity of the total CCDP for an SBLOCA to the failure probability of aggressive cooldown.

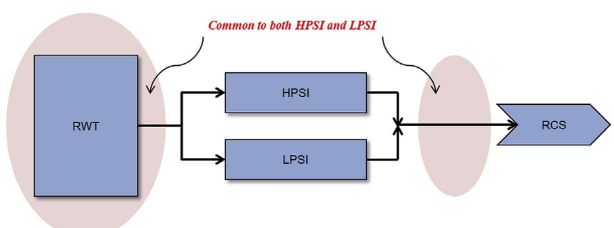

Fig. 6. Conceptual structure of the HPSI and LPSI with respect to the RWT and RCS.

of aggressive cooldown (Fig. 5). Based on these results, the core damage potential can be significantly reduced if aggressive cooldown can be performed highly reliably after an SBLOCA or SGTR combined with failure of HPSI.

It is important to understand how MCR operators perform aggressive cooldown in this scenario. After the reactor trip caused by an SBLOCA or SGTR, MCR operators are required to perform standard post-trip actions (SPTAs), diagnosis tasks, optimal recovery procedures (ORPs), and finally, functional recovery procedures (FRPs) before they initiate aggressive cooldown. The maximum cooldown rate is limited to 56 °C/hr (100 °F/hr), which further reduces the available time to initiate aggressive cooldown. Both the placement of aggressive cooldown in the EOPs and the limit on the maximum cooldown rate are challenges MCR operators may face in successfully performing aggressive cooldown in time.

Based on the importance of aggressive cooldown in minimizing risk as described in Section 3, a higher priority given to aggressive cooldown would increase the reliability of aggressive cooldown and hence, significantly reduce the core damage potential. Thus, the overall risk of the plant is also expected to be reduced.

Of course, it should be clearly recognized that EOPs for SBLOCAs and SGTRs are intended to manage various accident scenarios. For example, EOPs for a LOCA must consider not only SBLOCAs, but also LOCAs with larger break sizes, such as medium break LOCA (MBLOCA) and large break LOCA (LBLOCA), which do not require initiation of aggressive cooldown. However, considering that aggressive cooldown was found to be important for mitigating SBLOCA and SGTR situations, it is recommended that EOPs for LOCAs and SGTRs be improved to reflect the relative importance of aggressive cooldown on plant risk.

5. Conclusions

After identifying that the CDF has a linear relation with the failure probability of aggressive cooldown, we quantified the variability of plant risk on operators' failure probability of the timely initiation of aggressive cooldown using the PSA model for a nuclear power plant. We found that the CDF of the plant has a linear relation with the failure probability of aggressive cooldown and may decrease by up to 10% if aggressive cooldown can be performed highly reliably after occurrence of an SBLOCA or SGTR combined with total failure of HPSI. Failure of the MCR operators to perform aggressive cooldown within the success criteria occurred in 4 of the 20 highest risk core damage scenarios. Its Fussel-Vesely importance was found to have the 11th highest ranking among more than 6,000 basic events.

Based on the CCDP results for SBLOCAs and SGTRs, total failure of HPSI combined with failure of the MCR operators to initiate aggressive cooldown within the success criteria was found to have the highest risk ranking as well as being the dominant potential core damage scenario. Therefore, the core damage potential can be gradually reduced if aggressive cooldown can be more reliably performed by adopting measures such as improvement of EOPs and training of MCR operators with specific focus on timely initiation of aggressive cooldown.

It should be noted that the focus of this paper is to derive and provide the relation between the HEP of aggressive cooldown and possible increase and decrease in CCDPs for SBLOCAs and SGTRs. Even though the HEP of aggressive cooldown is changed or other HEPs are under consideration, the equations and the interpretation of them will be still valid and provide the variability of plant risk depending on the HEP under consideration.

Considering the importance of aggressive cooldown in reducing plant risk demonstrated by these results, we recommend conducting more detailed analyses of aggressive cooldown so that our understanding of this important topic can be broadened. Evaluation of the distribution of the maximum allowed time for MCR operators to initiate aggressive cooldown, the expected distribution of break size for SBLOCAs and SGTRs, and the distribution of the expected time for MCR operators to initiate aggressive cooldown may be included in such analyses.

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