Analysis of operator available time for responding to accident situations in a digitalized main control room

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Abstract: After the occurrence of an accident, operators' correct understanding of the situation and timely responding actions are important in maintaining the safety of nuclear power plants. Depending on the operator available time, the situation awareness and hence whether the accident situation is properly managed or not can be determined. In this paper, the operator available times for several accident situations involving small break loss of coolant accident (SBLOCA), loss of feedwater (LOFW), excessive steam dump event (ESDE) are evaluated using a simulation code. The results of this analysis can be used as basis for estimating the operators' failure probability in a digitalized main control room of a nuclear power plant..
Keyword: Operator action time, SBLOCA, LOFW, ESDE

1 Introduction

Appropriate measure by operators is important to maintain the safety of nuclear power plants. Since situation awareness of main control room operators plays an important role in responding to accident situations, it is important to analyzing the situation awareness of digital main control room operators of advanced nuclear power plants in an integrated manner with consideration of diverse information. For this purpose, it is important to analyze operators' manipulation characteristics in digital main control room of nuclear power plants such as important operators' manipulations and human error potential n digital main control room of nuclear power plants.

Operator action time affects transient condition and hence determines whether reactor safety can be maintained or not. Therefore, it is important to know how much time is available for the operators and how much time is required to take actions.

In this paper, in order to evaluate the available time of operators for responding to accident situation, thermal-hydraulic (TH) analysis is performed for three accident situations. First, a small break loss of coolant accident (SBLOCA) with the failure of all safety injection (SI) pumps. In such a situation, rapid reactor coolant system (RCS) coolding and depressurization by opening atmospheric dump valves (ADVs) is necessary. Previous researches for this accident situation include Palo Verde Individual Plant Examination (IPE)[1], Lim et al. [2], Lee et al.[3], and Kim et al.[4]. Second, loss of feedwater (LOFW) accident where feed and bleed (F&B) operation becomes necessary is analyzed. Previous researches for this accident situation include Hong et al.[5] and Park et al.[6]. Lastly, an excessive steam dump event (ESDE) with anticipated transient without scram (ATWS) is analyzed which requires operators' manual reactor trip.

The accident situations are analyzed for the operators in a digitalized main control room in an Advanced Power Reactor (APR) 1400 nuclear power plant. Personal Computed TRansient ANalyzer(PCTRAN) is used as a simulation code which can simulate various accident situations that may occur in nuclear power plants.

2 Analysis of various accidents

2.1 Small break loss of coolant accident

2.1.1 Event tree of SBLOCA

An event tree of SBLOCA with small break size from 0.5 to 2 inches on pipes in the primary system of nuclear power plant is shown in Figure 1. When SBLCOA occurs, reactor trip signal is generated by reactor protection system (RPS). If RPS does not work properly, the situation progresses to anticipated transient without scram (ATWS). After the reactor trip by RPS, SI is initiated and secondary heat removal will be conducted by using auxiliary feedwater (AFW). In such a situation, operators may open ADVs and conduct rapid secondary heat removal also known as aggressive cooldown. However, the event may result in peak cladding temperature (PCT) above 1204℃ and the potential for core damage exists depending on operator action time.[2] Thus, operator's maximum available action time is important in evaluating safety of nuclear power plants.

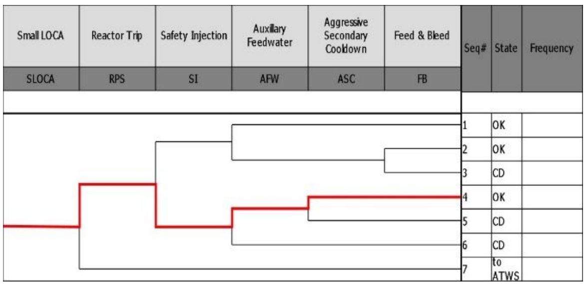

Fig.1 Event tree for SBLOCA

In Palo Verde Individual Plant Examination (IPE)[1], the success criteria of aggressive cooldown is given as operators taking actions within 15 minutes. Lee et al.[3] conducted TH analysis of SBLOCA for Optimized Power Reactor (OPR)1000 model, depending on break size and operator action time. Kim et al.[4] conducted feasibility analysis for operator action time of aggressive cooldown.

2.1.2 Analysis of SBLOCA

Under the situation that an SBLOCA occurs in APR1400 combined with the failure of all SI pumps, the supply of AFW and aggressive secondary cooldown need to be provided, as indicated in red-colored line in Figure 1. In this success path, PCT should not exceed 1204℃ and maximum cooldown rate should be less than 56℃ per hour to prevent pressurized thermal shock. Timely operator action in this success path is important and therefore TH analysis is performed to find out operators' available time for responding to the situation.

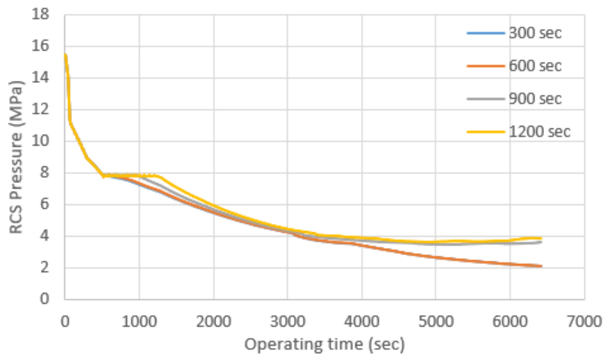

Fig.2 RCS Pressure of SBLOCA

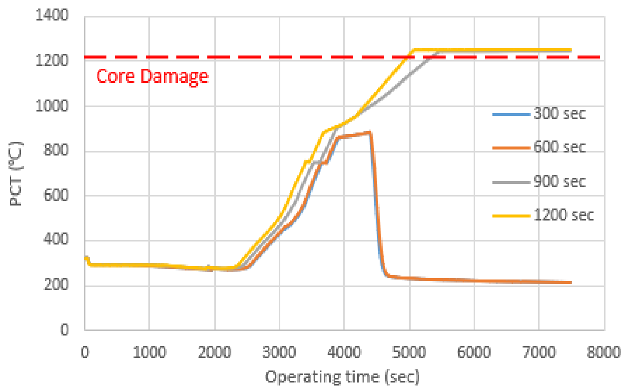

Fig.3 PCT of SBLOCA

When SBLOCA with break size of 2 inches in diameter occurs, reactor trip would occur in about 30 seconds. If SI pumps are not working, operators need to open ADVs for rapid RCS cooldown and depressurization. Depending on operators' action time to open ADVs, the changes in RCS pressure and PCT are shown in Figure 2 and Figure 3, respectively. Four cases of operator action time are analyzed from 300 seconds to 1200 seconds after reactor trip. It can be seen in Figure 2 that in all four cases RCS pressure decreases as operators open ADVs. However, if operators opened ADVs later than 900 seconds, it is found that PCT exceeded 1204℃ and hence the success criteria did not met. If operators open ADVs prior to 600 seconds, can prevent core damage may be prevented by reducing RCS pressure to safety injection tank (SIT) injection pressure. Therefore, it can be seen that operators' need to open ADVs prior to 600 seconds not to exceed PCT limit and maximum cooldown rate.

2.2 Loss of feedwater

2.2.1 Event tree of LOFW

An event tree of LOFW accident combined with the failure of all AFW pumps is shown in Figure 4. When LOFW accident occurs and reactor trip is successful, heat is supposed to be removed through secondary system with AFW. However, if secondary heat removal with AFW is failed, F&B operation needs to be conducted by opening pilot operated safety relief valves (POSRVs) and operating safety injection pumps.

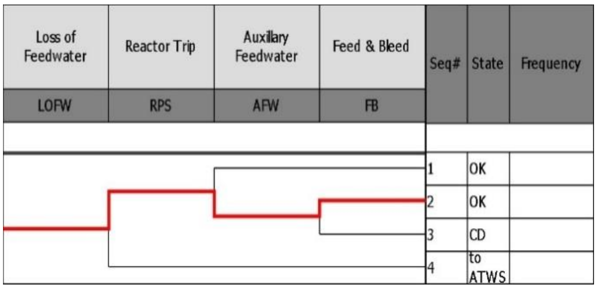

Fig.4 Event tree of LOFW

2.2.2 Analysis of LOFW

Hong et al.[5] performed TH analysis of LOFW accident depending on the capacity of FB operation. Park et al.[6] performed TH analysis on F&B operation by varying operator action time for APR1400 and concluded that two POSRVs and two SI pumps are sufficient for F&B operation during LOFW accident.

Four cases with different operator action time are analyzed and RCS pressure and PCT as functions for time are shown in Figure 5 and Figure 6, respectively. As operators' take actions earlier, the RCS pressure decreases and PCT also decreases due to injection by SI pumps. However, when operators' action is delayed, it is found that PCT may reach above 1204□ despite the decrease in RCS pressure. The boundary of the operator action time determined with the PCT limit is found to be between 5560 seconds and 5660 seconds. Therefore, it can be concluded that F&B operation need to be initiated prior to 5560 seconds.

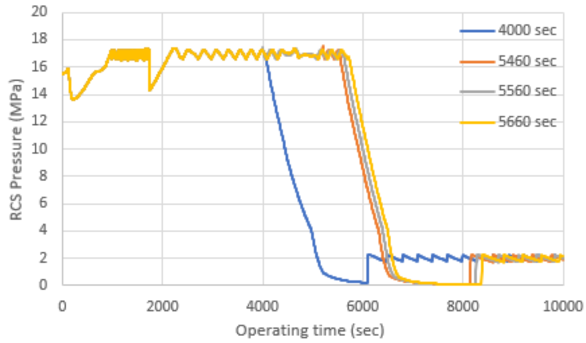

Fig.5 RCS Pressure of LOFW

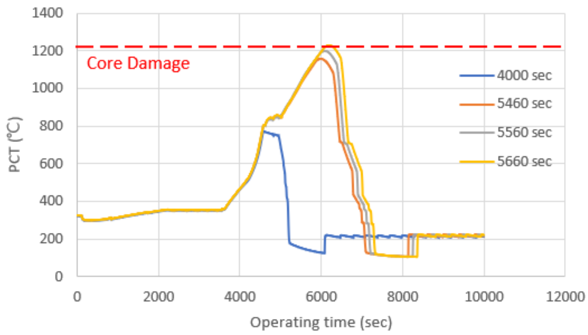

Fig.6 PCT of LOFW

2.3 Excessive Steam Dump Event

2.3.1 Event tree of ESD event

Figure 7 shows an event tree for Excessive Steam Dump Event (ESDE) in which steam flow in the secondary system is excessively increased by steam line break. When an ESDE occurs, RPS is supposed to trip the reactor and SI pumps are supposed to operate to control the reactivity. If RPS fails to trip the reactor automatically, ATWS situation need to be considered. Thus, in the case of automatic reactor trip failure, operators need to trip the reactor manually. It is assumed that containment spray (CS) is automatically initiated to reduce containment pressure.

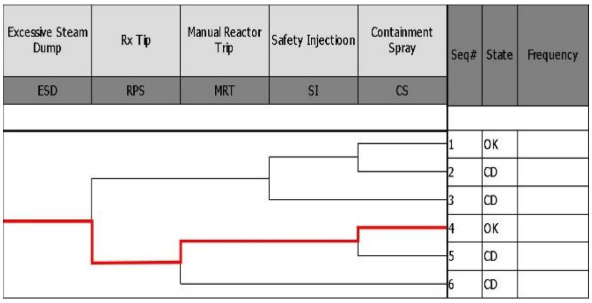

Fig.7 Event tree of ESDE

2.3.2 Analysis of ESDE

In this paper, TH analysis of the containment pressure is performed by varying break size and operator action time under ESDE with the failure of automatic reactor trip. As shown in Figure 8, if the break size is small, it is possible to mitigate the increase of containment pressure without reactor trip. However, when the break size is large, the containment pressure exceeds the design pressure (0.515MPa) if operators fail to timely trip the reactor manually. It is found that CS is not sufficient to properly reduce containment pressure in this situation. Therefore, it is important for the operators to trip the reactor manually as soon as possible in order to maintain the safety of the containment.

Figure 9 shows the change in containment pressure depending on operator action time. The break size in the secondary side is assumed to be $500cm^2$ with CS in operation. It is found that the containment pressure does not exceed the design pressure if manual reactor trip occurs prior to 390 seconds.

As shown in Figure 10, it is confirmed that CS also affects the integrity of containment. There are three cases depending on capacity of CS. The analysis is conducted for three cases, (1) two CS trains are operating normally, (2) one CS train fails, and (3) no CS train is available. For the specific case shown in Figure 10, it is noticed that CS system is as important as the operator action time in ESDE combined with the failure in automatic reactor trip by RPS.

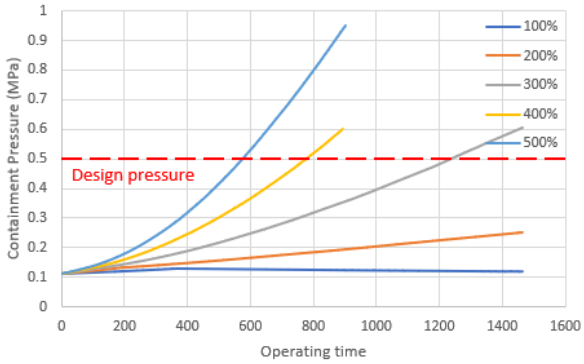

Fig.8 Containment pressure of ESDE depending on break size

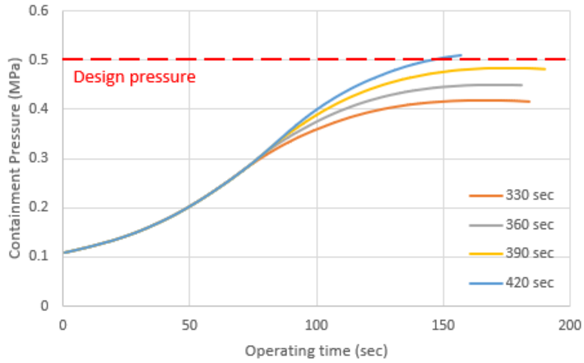

Fig.9 Containment pressure of ESD event depending on operation action time

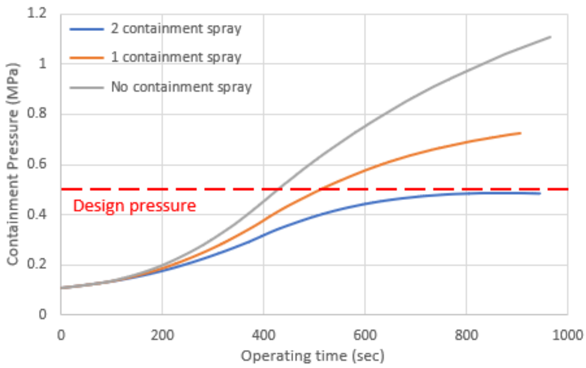

Fig.10 Containment pressure of ESD event depending on containment spray

3 Conclusion

Operator available time was estimated for accident situations involving SBLOCA, LOFW, and ESDE. Under the situation of SBLOCA combined with the failure of SI pumps, it is analyzed that operators' available time to open ADVs for rapid RCS cooldown and depressurization is less than 600 seconds. Under LOFW accident combined with the failure of AFW, it is analyzed that operators' available time to initiate F&B operation is less than 5560 seconds. In the situation of ESDE combined with the failure of automatic reactor trip, it is found to be important to trip the reactor manually when break size is more than a certain size. It is also found that CS plays an important role in mitigate the containment pressure, no matter whether the reactor is tripped or not. During such a situation, operator available time is the importance of CS is evaluated while varying the break size in the secondary side. This paper also provides simplified event trees for the accident situations and mitigation actions to help readers understand the type of accident sequences being analyzed.

With the estimation of operator available time in the accident situations being analyzed, it is expected that the analysis results will be used as a basis for analyzing the situation awareness of human operators in digitalized main control rooms as well as estimating the operators' failure probability in taking such accident mitigation actions.

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