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Analysis of Inadvertent Operation of the Emergency Core Cooling System During Shutdown Cooling System Operation on APR 1400 Using SPACE Code

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1. Introduction

During normal operation of nuclear power plant, an unexpected increase in reactor coolant system (RCS) inventory can occur. The injected coolant can lead to overpressure in the RCS, potentially compromising the integrity of the RCS pressure boundary (RCPB). Brittle fracture is a particular concern during low temperature RCS conditions such as startup or shutdown. To mitigate this risk, low temperature overpressure protection (LTOP) relief valves are installed in the shutdown cooling system (SCS). These valves ensure that RCS pressure never exceeds 20% of preoperational hydrostatic test pressure when the RCS temperature falls below the minimum service temperature, mandated by American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) Section III, Appendix G, Article G-2222, (c) [1].

Inadvertent operation of emergency core cooling System (IOECCS) can cause an increase in RCS inventory. If the IOECCS occurs while the SCS is isolated, safety injection (SI) can only begin when the RCS pressure is lower than the shutoff head pressure of the SI pump. In this scenario, the RCS pressure initially rise until it equals to the shutoff head pressure of the SI pump. On the other hand, if the IOECSS occurs during SCS operation, such as during plant shutdown, the LTOP relief valve will activate and mitigate RCS pressure surges. Therefore, the analysis of the IOECCS during SCS operation should focus on overpressure protection by the LTOP relief valve. There are some previous studies analyzing the overpressure protection at low temperature through LTOP relief valve using various methodologies and computer codes [2,3,4].

Korea Electric Power Corporation Engineering and Construction Company Inc. (KEPCO E&C) developed a non-loss of coolant accident (Non-LOCA) safety analysis methodology using Safety and Performance Analysis CodE for nuclear power plants (SPACE). This methodology was applied to the Advanced Power Reactor 1400 MWe (APR1400) and received approval from Korea Institute of Nuclear Safety (KINS) in 2017 [5]. Since the IOECCS is also a Non-LOCA event, employing SPACE code for the safety analysis of the IOECCS is appropriate approach.

This paper describes the analysis of IOECCS during SCS operation on APR1400 using SPACE code, focusing on the overpressure protection by the LTOP relief valve. The initial task identifying the location with the maximum pressure in the RCS was executed. Subsequently, the sensitivity analysis based on the initial conditions in the range of limiting condition of operation (LCO) was conducted. Finally, the highest RCS peak pressure and the LTOP relief valve response in the IOECCS during SCS operation on APR1400 was investigated.

2. Methodology

The additional modeling of SCS line and LTOP relief valve was incorporated into that of APR1400 nuclear steam supply system (NSSS) within the Non-LOCA safety analysis methodology for APR1400 with the SPACE code. Figure 1 illustrates the node configuration of APR1400 NSSS used in this study. Only one LTOP relief valve along with its upstream SCS line is considered to be conservative in terms of RCS overpressurization. The reactor coolant discharged through the LTOP valve is assumed to be released to atmosphere. At the accident initiation, both the SI and charging flows are assumed to be injected to the RCS.

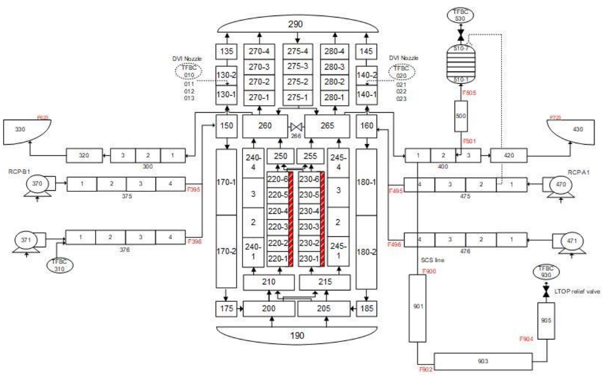

Fig. 1. SPACE nodalization of APR1400 NSSS incorporating the SCS line with one LTOP relief valve.

Table I describes the detailed parameters used for modeling of LTOP relief valve. The set pressure of 3.80 MPa (550.7 psia) is incorporated, which is obtained by adding 1% (6 psi) of measurement error associated with valve opening pressure to the design set pressure of 3.76 MPa (544.7 psia). Considering 3% maximum allowable tolerance as specified ASME Code for the opening pressure, the LTOP relief valve is modeled to initiate instantaneously with 30% of the full-open position at 103%

of the set pressure. Subsequently, the LTOP relief valve is opened linearly to full-open position at 10% accumulation of the set pressure. The capacity of the LTOP relief valve is set to the minimum capacity of 29,337 L/min (7,750 gpm).

Table I: The LTOP relief valve modeling description

Parameters	Value
Set pressure, MPa (psia)	3.80 (550.7)
Tolerance, % of set pressure	3
Accumulation, % of set pressure	10
Capacity, L/min (gpm)	29,337 (7,750)

3. Results and Discussion

3.1 Identification of the maximum RCS pressure location

To identify the location of the maximum RCS pressure during the IOECCS, the pressure at key locations within the RCS was analyzed, including the reactor vessel (RV) bottom, hot leg, cold leg, pressurizer (PZR), and upstream of the LTOP valve. As shown in Figure 2, the maximum pressure was observed as 4.25MPa (616.5 psia) at the RV bottom. The pressure differences among the RCS key locations result from the hydrostatic head caused by the elevation.

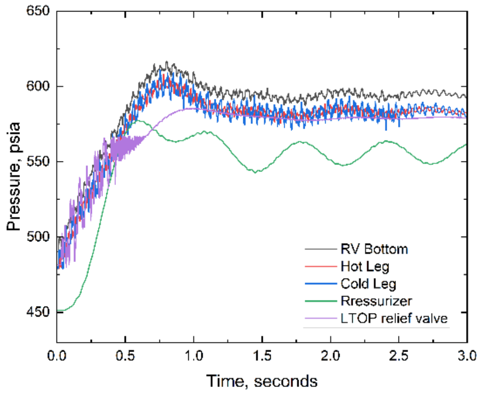

Fig. 2. The pressure behaviors at the RCS key locations during IOECCS.

3.2 Sensitivity study of initial conditions

The sensitivity studies on the RCS pressure and temperature were performed to investigate the effect of initial conditions on RV bottom peak pressure during the IOECCS. The analysis considered the operating conditions of the SCS, with the RCS pressures below 3.10 MPa (450 psia) and the RCS temperatures ranging from 322 K (120 ^{o}F) to 450 K (350 ^{o}F). The initial condition with the maximum RCS pressure and the minimum core inlet temperature is expected to be the most conservative case, since this combination would maximize the hydrostatic had due to the elevation. This expectation was confirmed by Table II which summarizes the RV bottom peak pressure during the IOECCS for each combination of initial RCS pressures and core inlet temperatures. The highest RV bottom peak pressure was obtained at the initial RCS pressure of 3.10 MPa (450 psia) and the initial core inlet temperature of 322 K (120 ^{o}F).

Table II: The summary of the RV bottom peak pressures during the IOECCS at combinations of initial RCS pressure and core inlet temperature.

Initial RCS pressure, MPa (psia)	Initial core inlet temperature, K (^{o}F)	RV bottom peak pressure, MPa (psia)
1.72 (250)	322 (120)	4.21 (610.6)
	394 (250)	4.20 (609.0)
	450 (350)	4.15 (601.4)
2.41 (350)	322 (120)	4.23 (614.3)
	394 (250)	4.21 (610.7)
	450 (350)	4.15 (602.0)
3.10 (450)	**322 (120)**	**4.25 (616.5)**
	394 (250)	4.21 (610.5)
	450 (350)	4.15 (601.5)

3.3 Overpressure protection during the most limiting IOECCS

The analysis for the most limiting IOECCS was performed to evaluate the effectiveness of the overpressure protection by the LTOP relief valve. To maximize the predicted peak pressure at the RV bottom, several conservative assumptions and initial conditions were employed. Table III summarized the major assumptions and initial conditions. The initial RCS pressure of 3.10 MPa (450 psia) and the initial core inlet temperature of 322 K (120 ^{o}F) were set based on the sensitivity studies conducted within this work. Moreover, for conservative analysis, the PZR water level was assumed to be solid with respect to the RCS peak pressure, and SI and charging flow temperatures were set to their minimum design values: 283 K (50 ^{o}F) and 289 K (60 ^{o}F), respectively. The maximum flow rates of SI and charging flows were also applied to the analysis. On the other hand, the letdown line is considered to be isolated. Additionally, the LTOP relief valve serves as the only exit path from the RCS.

Table III: Major assumptions and initial conditions of the most limiting IOECCS

Parameters	Value
RCS pressure, MPa (psia)	3.10 (450)
PZR water level	Solid
Core inlet temperature, K (^{o}F)	322 (120)
SI flow temperature, K (^{o}F)	283 (50)
Charging flow temperature, K (^{o}F)	289 (60)
SI flow rate	Maximum (4 SI pumps)
Charging flow rate	Maximum
Letdown flow rate	Zero

Figure 3 presents the discharge flow rate of the LTOP relief valve and the RCS inflow rate, which is the sum of the SI flow and the charging flow. The opening of the LTOP relief valve begins at 0.4 seconds. The discharge flow increases rapidly with the opening of the LTOP relief valve, peaking for about 1.0 seconds. After reaching its peak, the discharge flow rate gradually converges to the RCS inflow rate.

Figure 4 shows the RV bottom pressure behavior. When the IOECCS initiates, the SI flow is injected to the RCS resulting in a sharp escalation of the RV bottom pressure. Despite the LTOP relief valve being opened at 0.4 seconds, the mitigation effect is delayed leading to maintain the increase of the RV bottom pressure. At 0.8 seconds, corresponding to the moment when the discharge flow rate of the LTOP relief valve exceeds the RCS inflow rate, the RV bottom pressure reaches its peak of 4.25MPa (616.5 psia) lower than the RCS pressure limit of 4.31MPa (625 psia) for APR1400. This pressure limit is derived by applying the ASME BPVC Section III. App. G, Article G-2222 to APR1400 [1]. After that, the RV bottom pressure converges to a value slightly lower than the peak.

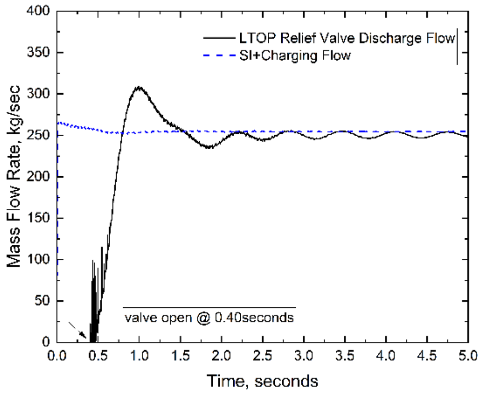

Fig. 3. The LTOP relief valve discharge flow rate and the RCS inflow rate (the sum of the SI flow and the charging flow) during the most limiting IOECCS

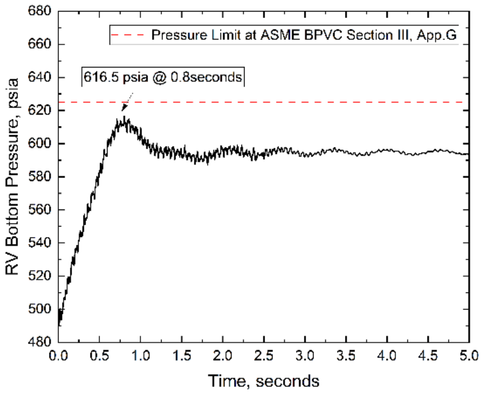

Fig. 4. The RV bottom pressure behavior during the most limiting IOECCS

4. Conclusions

In this study, the safety analysis of the IOECCS during the SCS operation on APR1400 was performed focusing on the overpressure protection at low temperature by the LTOP relief valve. Studies for the location of the maximum RCS pressure and conservative initial conditions were preferentially conducted. The highest RV bottom peak pressure during IOECCS was observed as 616.5 psia at 0.8 seconds, satisfying 4.31MPa (625 psia), which is the RCS pressure limit for the APR1400, required by ASME BPVC Section III, Appendix G, Article G-2222, (c). Consequently, this study indicates that the safety analysis using SPACE code is appropriate for the overpressure protection at low temperature during IOECCS. Further studies on other reactor types are scheduled to apply the implication of this study.

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