Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Sensitivity Analysis on Pressurizer Safety Valve Capacity for Overpressure Protection of an Integral Reactor

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1. Introduction

An integral reactor is composed of a steam pressurizer (PZR), fuels, Steam Generators (SGs), a surge line, and Reactor Coolant Pumps (RCPs) in a pressurized reactor vessel. In general, main purposes of the PZR are not only to maintain Reactor Coolant System (RCS) pressure, but also to accommodate the thermally induced volume change of the RCS during normal operation. In case of loss-of-load (the worst case transient), the RCS volume increases rapidly, and it results in intolerable overpressure in the primary system. The RCS can be protected from overpressure by discharging the saturated steam by opening Pressurizer Safety Valves (PSVs). The discharged steam through PSVs flows to a Reactor Drain Tank (RDT). The schematic diagram for PSVs, flow paths, and the RDT is depicted in Fig. 1.

In determining the PSV capacity (cross-sectional are), the worst case transient is considered with a delayed reactor trip. The PSVs are designed to maintain the RCS pressure below 110% of the design pressure [1]. In this study, numerical transient calculations were conducted to find the system pressure responses. Additionally, sensitivity analysis was also conducted to optimize PSV capacity.

2. Analysis Methods

Governing equations and models used in a numerical analysis are described in this section. The models include critical flow and polytropic process models. The analyses were conducted by using a commercial code (MATLAB).

2.1 Governing Equations

The RCS, surge line including buffer region, and PZR are enclosed inside a pressurized reactor vessel. Thus, coolant mass could be transferred between the RCS and PZR through the surge line. This relation could be described in Equation 1. A mass change rate in PZR can be obtained by taking into account the coolant in-surging rate and steam discharge rate through the PSVs as in Equation 2.

$$\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_{\mathrm{RCS}} = -(\dot{m})_{\mathrm{Surge}} \qquad (1)$$

$$\left(\frac{\mathrm{d}m}{\mathrm{d}t}\right)_{\mathrm{PZR}} = (\dot{m})_{\mathrm{Surge}} - (\dot{m})_{\mathrm{PSV}} \qquad (2)$$

, where m and $\dot{m}$ stand for the quantity of mass in the control volume and mass flow rate at its boundary, respectively. The subscripts represent the control volumes or the boundaries.

The RCS temperature can be obtained by taking into account the heat generation rate in the reactor core, SG heat transfer rate, sensible heat of structures, and energy transfer rate of the surge flow. This relation could be expressed as follows:

$$\left(\frac{\mathrm{d}U}{\mathrm{d}t}\right)_{\mathrm{RCS}} = -(\dot{m}i)_{\mathrm{Surge}} + \dot{Q}_{\mathrm{RX}} - \dot{Q}_{\mathrm{SG}} - \dot{Q}_{\mathrm{Str}} \qquad (3)$$

, where $\dot{Q}$, i, and U stand for heat transfer rate in the control volume, specific enthalpy, and internal energy, respectively. The RX, SG, and Str stand for reactor core, steam generator, and structures, respectively.

2.2 Critical Flow Model

The PSVs are installed in a steam region of the PZR, and the saturated steam in the PZR is directly discharged to the RDT when PSVs are open. To calculate the discharging flow rate through the PSVs, the critical flow model [3] is used as follows:

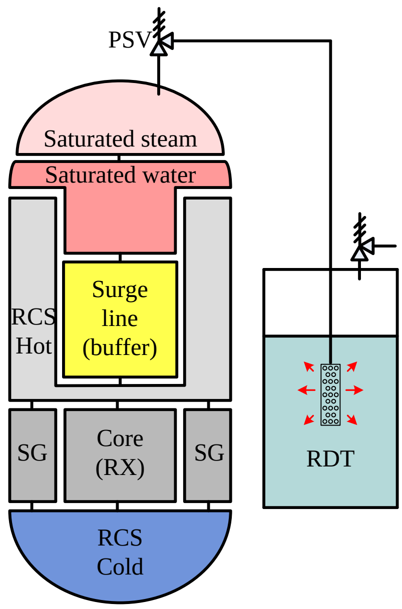

Fig. 1. Schematic Diagram of PSV for an Integral Reactor

$$(\dot{m})_{\mathrm{PSV}} = C_{\mathrm{d}} \cdot A \cdot \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{2(\gamma-1)}\right)} \cdot (\gamma \cdot \rho_{\mathrm{s}} \cdot P_{\mathrm{PZR}})^{1/2} \quad (4)$$

, where C_{d}, A, γ, ρ_{s} and P_{PZR} stand for discharge coefficient, cross-sectional area of the PSV, heat capacity ratio, density of saturated steam, and pressure of the PZR, respectively.

2.3 Polytropic Process

The steam region of the PZR is pressurized by in-surge flow during the worst case transient, and the transient results in the increase of pressure. In the out-surge transient, the steam region is depressurized, and it results in decrease of pressure. The polytropic process is used to find PZR behavior during these transients. The Equation for the polytropic process [2] is described as follows:

$$P_1(V_1)^{\mathrm{n}} = P_2(V_2)^{\mathrm{n}} \quad (5)$$

, where P, V, and n stand for pressure, volume, and polytropic index, respectively.

2.4 PSV capacities and Initial Conditions

The PSV capacities used for the sensitivity analysis are described in Table I. The capacities are varied from 20% to 240% of a target design value. The effects of different PSV capacities are specifically described in Section 3.

Normalized initial conditions for the transient calculations are described in Table II. Each parameter is normalized to the design value.

At onset of the loss-of-load transient, the reactor core and steam generators are operated at the maximum rated output plus three percent of uncertainty. Additionally, the initial pressure and initial steam volumes are set to be higher than normal operating conditions. As a result, those initial values result in the maximum heat-up and the maximum pressurization rate of the primary system. The maximum rates mean that the more severe accident is considered for the conservative calculation.

Table I: Normalized PSV Capacities

Case	Normalized PSV Capacity
A.PSV_0.2	0.2
A.PSV_0.4	0.4
A.PSV_0.6	0.6
A.PSV_0.8	0.8
A.PSV_1.0	1.0
A.PSV_1.2	1.2
A.PSV_1.4	1.4
A.PSV_1.6	1.6
A.PSV_1.8	1.8
A.PSV_2.0	2.0
A.PSV_2.2	2.2
A.PSV_2.4	2.4

Table II: Normalized Initial Conditions

Parameter	Name	Normalized Value
Pressure	PZR	0.92
	RCS	0.92
Temperature	PZR	0.95
	RCS	0.89
Volume	PZR (steam)	0.76
	PZR (water)	1.25
Performance	RX	1.03
	SG	1.03

2.5 Calculation Procedure

Calculation procedure for the PSV capacity is depicted in Fig. 2. The numerical calculation was conducted by using the MATLAB code which solves the governing equations with given conditions. The code algorithm is developed to calculate the pressure change of the primary system, density, discharge flow rate, surge flow rate, etc. The calculation results include the behavior of the integral reactor during the transient.

3. Calculation Results

In this study, a series of transient calculations are conducted with various PSV capacities. The pressure change during the transient is described in Section 3.1. Additionally, the results of sensitivity analysis are described in Section 3.2.

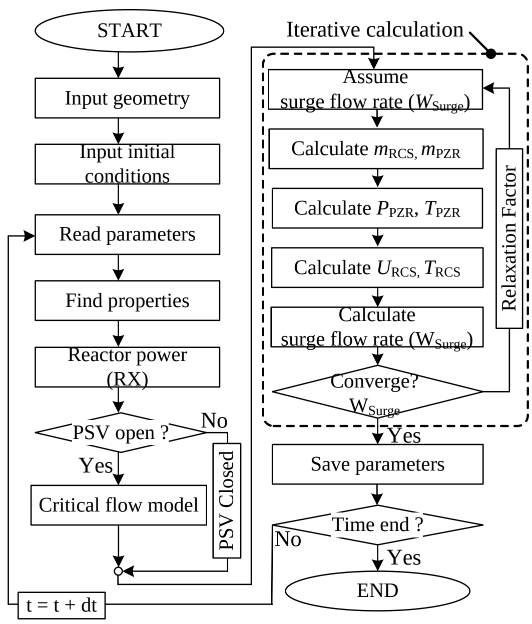

Fig. 2. Flow diagram for PSV calculation

3.1 Pressure change during loss-of-load transient

As time passes from 0 to 30 sec, the pressure change of the RCS is depicted in Fig.3. The peak pressure of the RCS remains below 110% of the design pressure during the worst case transient.

The pressure increases immediately after the transient occurred at 1.0 sec. The pressure reaches reactor trip setpoint at 7.5 sec. The reactor trip occurred at 9.1 sec, because the time delay of a reactor trip is set to be 1.6 sec. The PSVs are conservatively assumed to open at higher pressure than the opening setpoint by considering uncertainties and additional margins.

The saturated steam is discharged through PSVs, and the pressure increasing rate is reduced by discharging the steam. An inflection point, which defines the peak pressure(or maximum primary system pressure), occurred within several seconds after PSV opening. Finally, the pressure kept on decreasing continuously until the PSVs are closed.

3.2 Maximum primary system pressure

The pressure changes with varying PSV capacities are shown in Fig. 4. The trend of the peak pressures is depicted in Fig. 5. The rate of pressure decrease is negligible at 20% of the design capacity, even though PSVs are open. As the PSV capacity increases, the depressurization rate increases gradually.

In the cases from 20 - 60%, the peak pressures are still remained below 110% of design pressure. However, the depressurization rates are not sufficient for overpressure protection. As a result, relatively long time is required to recover the primary system pressure below the design pressure.

In the cases above 140%, the depressurization rates are sufficient. However, the amount of discharged steam could be excessive, and it results in the excessive increase of RDT capacity.

In the cases from 80 - 120%, the results of the peak pressure and the depressurization rates are acceptable. The peak pressures are maintained below 110% of the design pressure, and the primary system pressures can be recovered below the design pressure within 15 sec after the PSV opening.

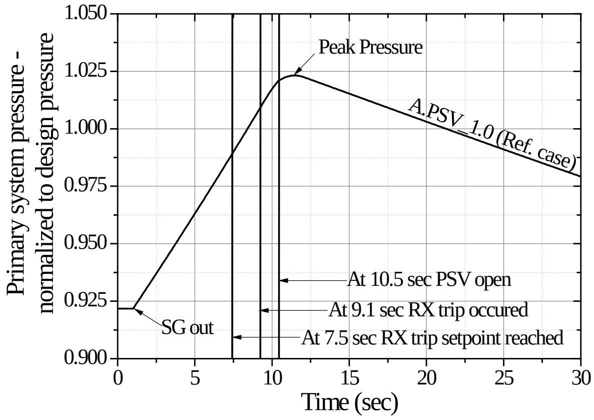

Fig. 3. Pressure change during loss-of-load transient

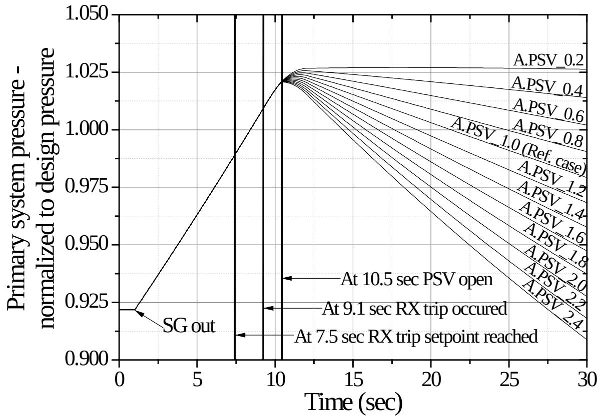

Fig. 4. Effect of PSV capacity

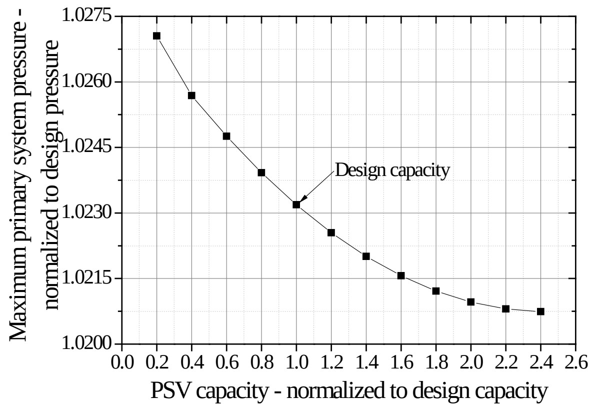

Fig. 5. Peak pressure with varying PSV capacity

3.3 Discharge flow rates through PSVs

The discharge flow rates with varying PSV capacities are described in Table III. As the PSV capacities increase, the discharge flow rates also increase linearly. This linear relation between PSV capacity and discharge flow rate is simply predicted by Equation (4).

Table III: Results of Normalized Discharge Flow Rates

Case	Normalized Discharge Flow Rate
A.PSV_0.2	0.201
A.PSV_0.4	0.402
A.PSV_0.6	0.601
A.PSV_0.8	0.801
A.PSV_1.0	1.000
A.PSV_1.2	1.199
A.PSV_1.4	1.398
A.PSV_1.6	1.596
A.PSV_1.8	1.795
A.PSV_2.0	1.994
A.PSV_2.2	2.193
A.PSV_2.4	2.392

4. Conclusion

In this study, transient calculations were conducted numerically to analyze the integral reactor which responses on the PSV opening. Additionally, sensitivity analyses were also conducted from 20 - 240% of PSV capacities for the optimization.

The peak pressures are maintained below 110% of the design pressure in all cases. These results satisfy the requirements that the primary system pressure shall be maintained by PSVs less than 110% of the design pressure during the most severe transient.

As the PSV capacity increases, the discharge flow rate also increases at the almost same rate. This relation can be calculated by using critical flow model. If the PSV capacity is too small, the depressurization rates are not enough for the overpressure protection. On the other hand, the excessive increase of the PSV capacity also results in the excessive design of the RDT capacity. As a result, the optimized PSV capacity is required for the overpressure protection of an integral reactor. In this study, the 80 - 120% of the design capacity is appropriate for the optimized PSV capacity.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) funded by the Korea government (MSIP) (No. NRF-2016M2C6A1930039).

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