Preliminary Evaluation on Optimum Range of Pressurizer Spray Flow Rate during Normal Power Operation of an Integral Reactor

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1. Introduction

An integral reactor is composed of steam pressurizer (PZR) and reactor coolant system (RCS) in a single pressurized reactor vessel. The PZR has spray system and the spray line that are connected from CVCS letdown line to the top of the PZR. The reactor coolant (borated water) is continuously provided through the spray line in order to satisfy the Boron concentration equilibrium between the PZR and the reactor coolant loop during normal power operation.

The PZR heaters are installed in the PZR; the PZR heaters are operating automatically (or manually) to compensate the heat losses due to spray flow, Control Rod Drive Mechanisms (CRDMs), and other insulation thermal transferences. In this study, the PZR spray flow rates are calculated with varying valve opening area, and the amount of heat losses are obtained in each case. Additionally, the evaluation on pressurizer spray flow rate is conducted to find the optimum range that satisfies the minimum heat loss and Boron concentration equilibrium.

2. Methods and Results

Governing equations and method used in this analysis are described in this section. It also includes system description, results as well as optimum operation range for normal power operation.

2.1 System Description

Fig. 1 shows the simplified schematic diagram of main spray lines for an integral reactor. The PZR is placed at the top-side of the integral reactor, and four (4) spray nozzles are installed to Reactor Closure Head Assembly (RCHA). PZR spray system is used to provide reactor coolant (borated water) from the CVCS letdown line in order to satisfy the boron equilibrium in the PZR region. The spray nozzles are shared with the main spray line and the auxiliary spray line. For simple analysis, the spray line has been divided into 8 sections by points (a), (b), (b1), (b2), (b3), (c), (d), and (e) as shown in Fig. 1. Each section represents the point of interest for the calculation. PZR spray control valve between sections (b1) and (b2) is used to control the flow rate by changing valve opening area.



Fig. 1. Simplified schematic diagram for pressurizer and main spray line of an integral reactor.

2.2 Calculation Methodology

The driving force of main spray flow is provided by Reactor Coolant Pump (RCP) head, and the main spray flow rate is determined by balancing the flow resistance of the main spray line and the pressure difference between RCS and PZR. The CVCS letdown nozzle pressure and pressure drop of the main spray line are calculated for the main spray flow rate. The PZR spray control valve in the spray line is designed to control the spray flow during normal operation.

By balancing pressure between the two points (letdown and spray nozzle), Pressure drop calculation for the spray line can be conducted by using Equation (1).

$$\frac{P_{(1)}}{\rho g} + \frac{V_{(1)}^{2}}{2g} + h_{(1)} = \frac{P_{(2)}}{\rho g} + \frac{V_{(2)}^{2}}{2g} + h_{(2)} + H_{\rm L}, \tag{1}$$

where V, h, H_L , and ρ stand for flow velocity, height, head loss, and density, respectively. Equation (1) can be transformed into Equation (2) to find the pressure at any point in the spray line.

$$P_{(2)} = P_{(1)} + \frac{\rho}{2} (V_{(1)}^{2} - V_{(2)}^{2}) + \rho g \Delta h_{(1)-(2)} + \rho g H_{L}$$

= $P_{(1)} + [\Delta P_{FV} + \Delta P_{EL} + \Delta P_{L}]$ (2)

where $\Delta P_{\rm FV}$, $\Delta P_{\rm EL}$, and $\Delta P_{\rm L}$ stand for pressure drop by flow velocity, elevation, and other fitting losses (piping, valve, bend, tee, and reducer), respectively. Fitting pressure loss correlations and coefficients can be found in References [1] and [2].

The amount of heat loss by lower temperature of the PZR spray flow can be obtained by using Equation (3).

$$(\dot{Q}_{\text{Spray}})_{\text{Net}} = \dot{m}_{\text{Spray}}^{W} \cdot (\dot{i}_{\text{Spray}} - \dot{i}_{\text{Surge}})$$
 (3)

where $(\dot{Q}_{\text{Spray}})_{\text{Net}}$, \dot{m}_{Spray}^W , i_{Spray} , and i_{Surge} are amount of heat loss by spray, spray mass flow rate, and specific enthalpy for spray and surge regions, respectively.

Using the above equations, the pressure drop of spray line is calculated. Different valve opening area of PZR spray control valve is used as a variable to find the optimum flow range that will satisfy minimum heat loss and Boron concentration equilibrium during normal operation. The calculation results regarding Boron concentration are used in Reference [3]

2.3 Results

Fig. 2 shows the normalized pressure drop of each section in the spray line for fully open PZR spray control valve. The pressure at (a) is equal to the letdown pressure. It will be reduced up to pressurizer pressure at spay nozzle point (e). Points (b3), (c), and (d) shows pressure less than spray nozzle due to elevation pressure drop.

By controlling PZR spray control valve between sections (b1) and (b2), different spray flow rates are calculated. Fig. 3 shows normalized spray flow rate at fully (1), 3/4, 2/3, 1/2, 2/3, and 1/4 opening. Maximum main spray flow rate is 100% of allowable flow for fully open spray control valve. When the control valve opening area decreases, the flow will decrease until 40% for 1/4 valve opening. Fig. 4 shows normalized Boron concentration difference for different spray flow rates with corresponding normalized heat loss. Normalized Boron concentration difference data between PZR and reactor coolant for different spray flow rates are provided in Reference [3]. If the spray flow rate increases, heat loss also increases. On the other hand, the Boron concentration difference gradually decreases. The optimum range for main spray flow rate that will satisfy minimum heat loss with less Boron concentration difference is from 10% to 45% of allowable flow rate for normal operation.



Fig. 2. Normalized pressure drop in PZR spray line at each section.



Fig. 3. Normalized PZR spray flow rate for different valve opening area.



Fig. 4. Normalized PZR spray heat loss and maximum Boron concentration difference for different main spray flow rates.

3. Conclusions

Pressure drop calculation for main spray line is conducted for each section. PZR spray control valve is controlled at fully (1), ${}^{3}\!/_{4}$, ${}^{2}\!/_{3}$, ${}^{1}\!/_{2}$, ${}^{2}\!/_{3}$, and ${}^{1}\!/_{4}$ opening to find the effect on the heat loss as well as Boron concentration difference between PZR and reactor coolant loop. The maximum allowable main spray flow rate will be 100% of allowable flow for fully open spray control valve. The optimum range for main spray flow rate that will satisfy minimum heat loss with Boron concentration equilibrium is recommended from 10% to 45% of allowable flow rate for normal operation.

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