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# Flow Characteristics Analysis for the Chemical Decontamination of the Kori-1 Nuclear Power Plant

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Chemical decontamination of primary systems in a nuclear power plant (NPP) prior to commencing the main decommissioning activities is required to reduce radiation exposure during its process. The entire process is repeated until the desired decontamination factor is obtained. To achieve improved decontamination factors over a shorter time with fewer cycles, the appropriate flow characteristics are required. In addition, to prepare an operating procedure that is adaptable to various conditions and situations, the transient analysis results would be required for operator action and system impact assessment. In this study, the flow characteristics in the steady-state and transient conditions for the chemical decontamination operations of the Kori-1 NPP were analyzed and compared via the MARS-KS code simulation. Loss of residual heat removal (RHR) and steam generator tube rupture (SGTR) simulations were conducted for the postulated abnormal events. Loss of RHR results showed the reactor coolant system (RCS) temperature increase, which can damage the reactor coolant pump (RCP)s by its cavitation. The SGTR results indicated a void formation in the RCS interior by the decrease in pressurizer (PZR) pressure, which can cause surface exposure and tripping of the RCPs unless proper actions are taken before the required pressure limit is achieved.

Keywords: Kori-1 Nuclear Power Plant, Decommissioning, Chemical decontamination, Flow characteristics, Transient analysis, MARS-KS

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## 1. Introduction

Chemical decontamination for decommissioning NPP is the process of removing oxide films and metal oxide deposits from the interior surfaces of components and piping. This process is required for all major reactor coolant systems prior to the start of the main decommissioning activities to reduce the radiation exposure to workers during decommissioning and minimize the radioactive wastes. Basically, the main process can be divided into two groups: 1) dissolving of the oxide films and metal oxides via chemical reactions and 2) removal of the left-over and waste chemicals via filtration or ion exchange. The entire process is repeated until the desired decontamination factor is obtained. Depending on the chemicals to be injected, many different processes have been proposed and applied to components and systems for further operation or decommissioning of plant. As these processes have been conducted many times over previous years, the chemical processes can be advanced to be mature and well-defined. However, it has been noted that the application of these chemical-decontamination processes should be varied according to differing NPP types, system condition with configurations and, chemical reagents etc. [1].

The Kori-1 NPP, a 2-loop pressurized water reactor (PWR), was permanently shut down on June 18, 2017, and it is the first commercial NPP in South Korea entering the decommissioning phase [2]. Methodologies for the decontamination of Kori-1 NPP have been studied, and a chemical decontamination system has been developed and tested. In Ref. [3], decontamination technologies are reviewed and key considerations for planning of decontamination are described. In Ref. [4], chemical and mechanical techniques for primary system decontamination are compared. In Ref. [5], the operational concept of the full system chemical decontamination for Kori-1 is described based on obtained overseas experiences. In Ref. [6], a numerical analysis is conducted to examine the operation of the RHR system pump for providing the circulating flow rate. A research project considering the decontamination technology for the reactor coolant system and dismantled equipment is currently under development [7].

To achieve improved decontamination factors over a shorter time with fewer cycles, the appropriate flow characteristics should be provided. If the circulating flow rate is low, the dissolved metal elements could settle and become deposited, which results in hot spot formation or the plugging of tubes. As noted in Ref. [5-6], operating only the RHR pumps in chemical decontamination may not provide a sufficient flow rate, thus additional operation of the pumps would be required. Especially in Ref. [5], the both the flow velocity and Reynolds number are calculated to investigate the flow characteristics and low flow velocity and Reynolds number are found in steam generator tubes.

Moreover, if the reactor pressure vessel (RPV) and steam generators (SGs) are within the scope of the decontamination, operating of RCP is recommended. It has been shown that high flow rates yield improved decontamination results [8]. It is important to note that RCP operation requires several other considerations, e.g., system pressurization and RCP seal injection. Therefore, proper procedures should be provided to operators and workers. Transient analysis results would provide a valuable basis for preparing such procedures under various system conditions, including abnormal situations.

In this study, the flow characteristics of the Kori-1 NPP RCS for chemical decontamination operations is analyzed. In addition, representative transient events are considered for identifying anticipated transients to the system. First, a system model developed by MARS-KS (1.4 version) is prepared. MARS-KS is a computer code based on one-dimensional two-fluid formulation and widely used for thermal hydraulic accident analyses of light water reactors such as Loss of Coolant Accident, Loss of Feedwater, SGTR [9]. Second, for the steady-state analysis, the operational conditions (pressure and temperature) and flow characteristics (e.g., velocity and Reynolds number) are investigated. Third, the possible initiating events that result in transience

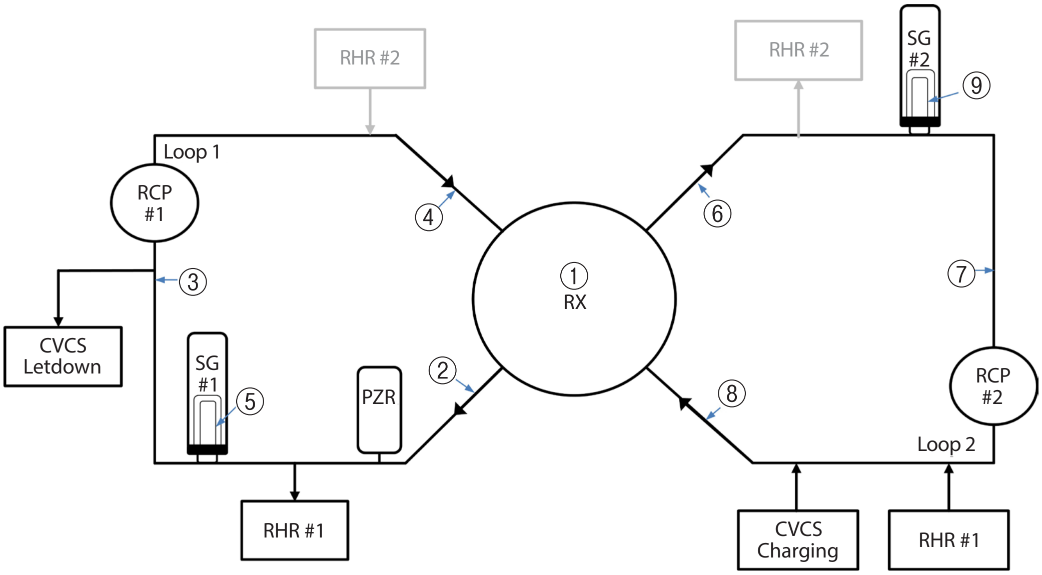

Fig. 1. Schematics of the Kori-1 RCS.

Table 1. RCS conditions

| Process | PZR Level [%] | RCS Temperature [°C] | RCS Pressure [bar] |
|---|---|---|---|
| Oxidation/Dissolution | 45 | 95 | 26.15 |

are identified and simulations are conducted. The timing of major events, rate of system condition changes and impacts with respect to the chemical process are examined.

## 2. Numerical modeling

The Kori-1 NPP is a 587-MWe PWR with 2 loops of Westinghouse-type. The primary systems included in the RCS decontamination are considered to be as follows: RPV, SGs, PZR, RCS piping, RCPs, residual heat removal system (RHRS) and chemical and volume control system (CVCS). The fuel is considered to have been removed and safety injection systems are excluded. It is assumed that the secondary sides of SGs are exposed to the atmosphere (dry conditions). The Kori-1 RCS considered in this study is presented in Fig. 1. Note that the RCS pressure may be controlled via nitrogen gas injection through the PZR. The temperature and flow rate can be obtained by using the RCPs. The RCS inventory and PZR level are controlled via CVCS letdown and charging. The target conditions for RCS chemical decontamination are shown in Table 1. The minimum operating pressure of RCP is 22 bar from the previous study [10]. Considering a margin, the operation pressure is determined as 26.15 bar. The chemical injection and decomposition facility are assumed to be connected to the RHRS return line, as shown in Fig. 2.

The MARS model is developed by modifying a model previously developed for accident analysis [11].

The components with control functions related to safety injections are removed. The parameters and control logics for simulating the decontamination process conditions are added. In Fig. 3, the nodalization of the Kori-1 RCS of MARS model is presented. In this study, the steady-state

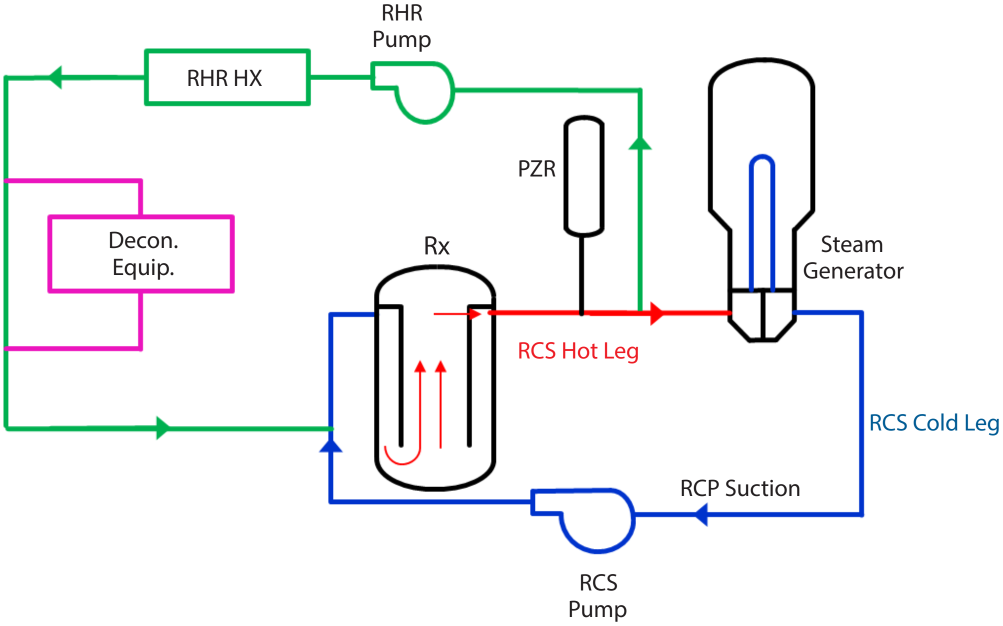

Fig. 2. Schematics of the chemical decontamination equipment connections.

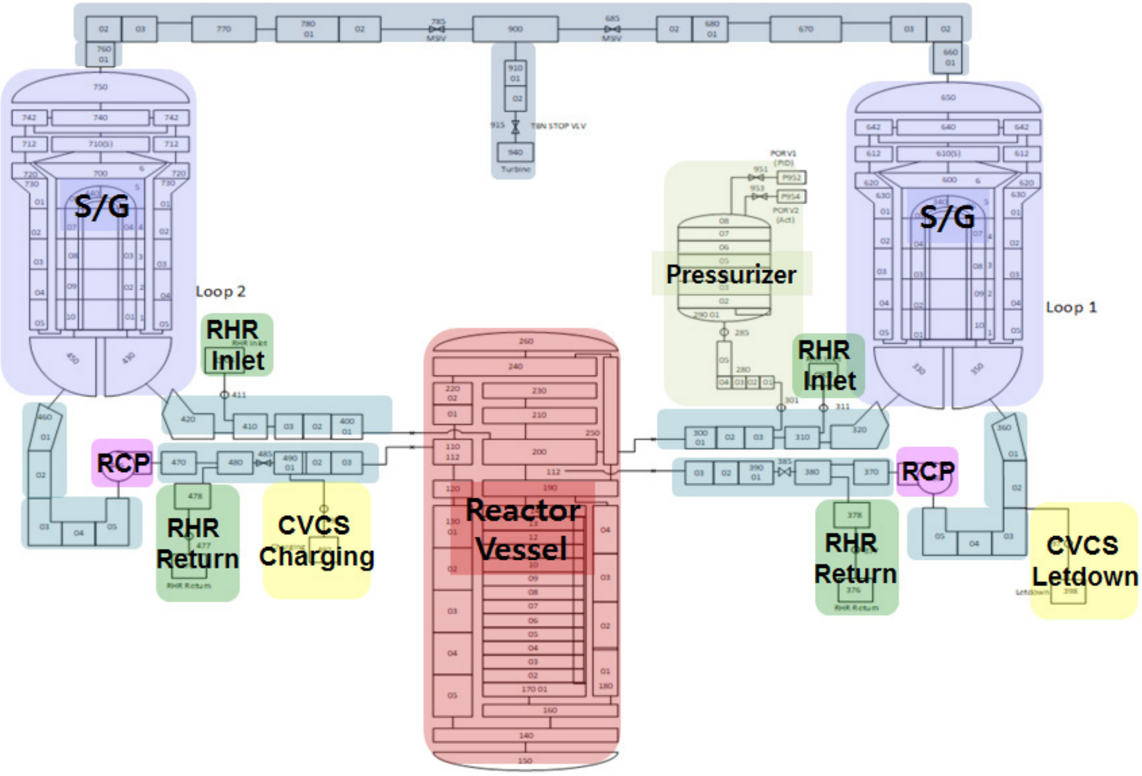

Fig. 3. Nodalization of the Kori-1 RCS MARS Model.

Table 2. Steady-state flow characteristics in the RCS

| Location Number | Description | Velocity [m·s$^{-1}$] | Reynolds Number |
|---|---|---|---|
| 1 | Reactor Vessel | 3.16 | $1.23\times10^5$ |
| 2 | Loop 1 Pipe (Reactor ~ SG) | 14.35 | $1.98\times10^7$ |
| 3 | Loop 1 Pipe (SG ~ RCP) | 14.22 | $1.96\times10^7$ |
| 4 | Loop 1 Pipe (RCP ~ Reactor) | 16.13 | $2.22\times10^7$ |
| 5 | Loop 1 SG Tube | 5.50 | $3.01\times10^5$ |
| 6 | Loop 2 Pipe (Reactor ~ SG) | 14.09 | $1.94\times10^7$ |
| 7 | Loop 2 Pipe (SG ~ RCP) | 14.25 | $1.97\times10^7$ |
| 8 | Loop 2 Pipe (RCP ~ Reactor) | 15.85 | $2.19\times10^7$ |
| 9 | Loop 2 SG Tube | 5.51 | $3.01\times10^5$ |

Table 3. Transient analysis cases

| Analysis Cases | Case Description | Plant Condition | | |
|---|---|---|---|---|
| | | RCP | CVCS | RHR |
| 1 | Loss of RHR | 2 EA Available | Available | Disabled |
| 2 | | 2 EA Available | Disabled | Disabled |
| 3 | SGTR | 2 EA Available | Available | Available |

and transient RCS conditions are considered. The other systems connected to the RCS, including the CVCS and RHR, are simplified for use as boundary conditions. Malfunctions in those systems are modelled using time-dependent user-specified components.

## 3. Numerical results and discussion

### 3.1 Steady-state operations

The flow characteristics under the chemical decontamination process conditions shown in Table 1 are analyzed. Two RCPs for loop 1 and loop 2, 1 train of the RHRS for removing heat induced by the RCP, and the CVCS for the RCS inventory control are operated. The flow velocities and Reynolds numbers in various RCS locations are summarized in Table 2. The location number is indicated in Fig. 1. As can be seen in Table 2, the Reynolds numbers in the RCS flow are larger than 100,000 in all regions, which indicates that a sufficient circulating flow rate in turbulent flow will be provided in the reactor vessel and SG tubes [12].

### 3.2 Transient analysis

Transient analyses are conducted for the postulated abnormal conditions. In order to determine the possible transient events, the initiating events considered in Emergency Operating Procedure (EOP) and Abnormal Operating Procedure (AOP) of Kori-1 and -2 are reviewed.

Most anticipated transient events are evaluated for this study and the events which have similar transient behavior are grouped and the representative event is derived. As a result, anticipated as commonly severe cases for system integrity are selected for representative transient analysis cases.

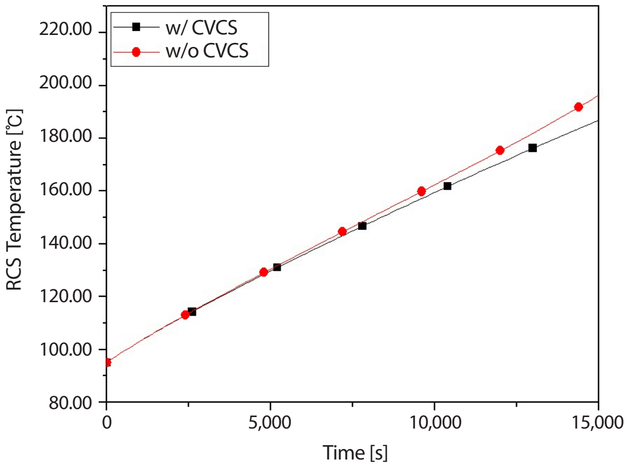

Fig. 4. RCS hot leg temperature–Loss of RHR.

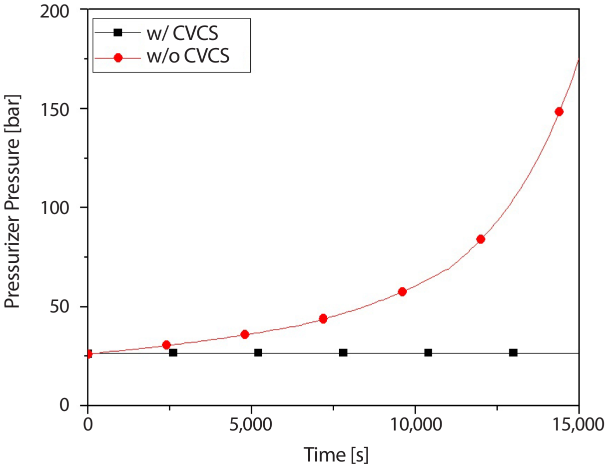

Fig. 5. PZR pressure–Loss of RHR.

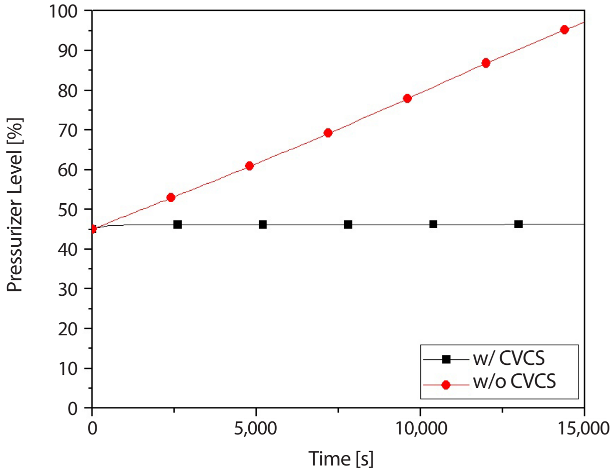

Fig. 6. PZR level–Loss of RHR.

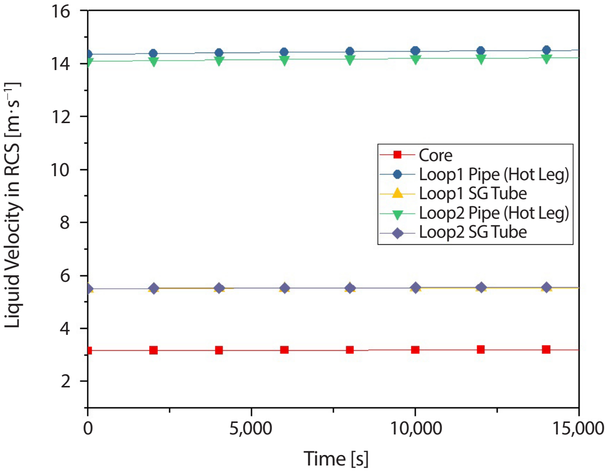

Fig. 7. RCS velocity–Loss of RHR.

As a representative case of a loss of heat removal, the loss of RHR is considered. For the loss of the RCS inventory, SGTR is considered. The analysis cases with system operations are summarized in Table 3.

### 3.2.1 Loss of RHR

The loss of RHR event could be initiated by an RHR pump failure, which results in RHRS isolation. Due to the insufficient removal of heat generated by the RCS operation, the pressure and temperature of the RCS would increase. As shown in Fig. 4, the RCS temperature would increase gradually due to the loss of heat removal by the RHRS. The RCS pressure and the PZR water level would be maintained if the CVCS is in operation to charge and letdown the flow control. Conversely, the RCS pressure and PZR water level would increase rapidly without CVCS operation (Fig. 5 and 6). The RCS flow rate remains the same as the steady-state rate because it is assumed that the RCP operates normally, even under transient conditions (Fig. 7). Regarding the decontamination process, there would not be significant degradation of decontamination performance because the circulating flow would be maintained with the RCP operation. However, it is necessary to restore the heat removal by the RHRS because the RCS temperature rise

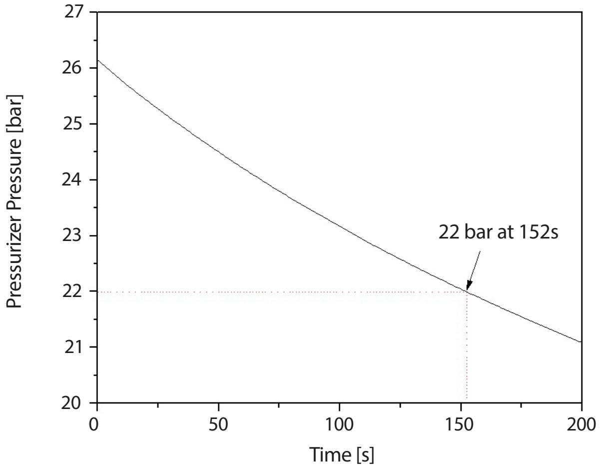

Fig. 8. PZR pressure–SGTR.

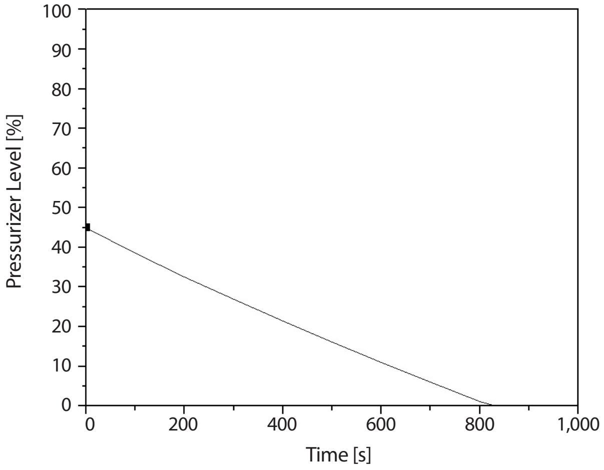

Fig. 9. PZR level–SGTR.

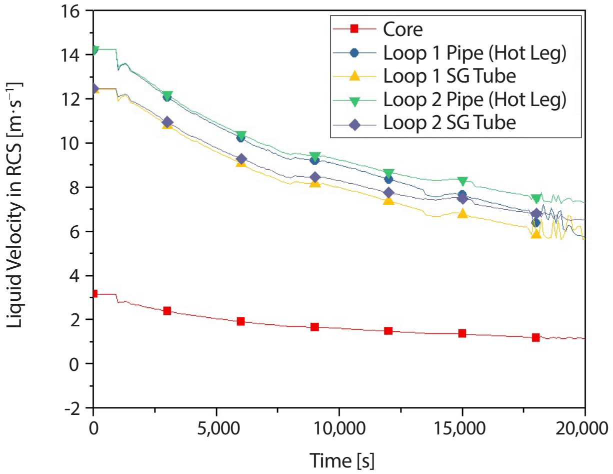

Fig. 10. RCS velocity–SGTR.

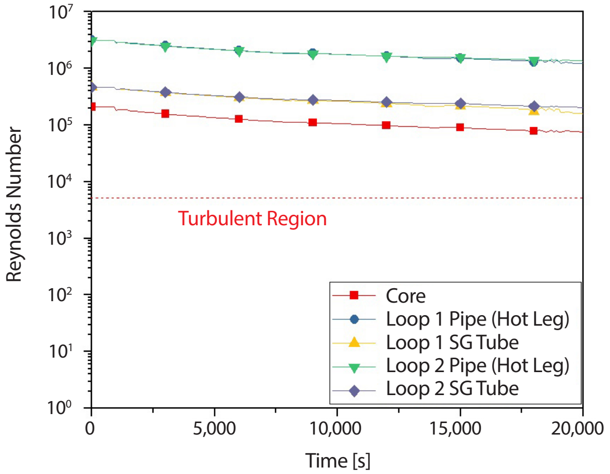

Fig. 11. Reynolds number–SGTR.

can cause cavitation, which can damage the RCPs. According to the simulation, the RCS temperature would be increased by 0.47°C·min$^{-1}$. Therefore, the RCS temperature would increase to 109°C after 30 min of heat removal. Assuming that the pump cavitation would occur over 200°C, there would be sufficient time for the operators to take proper action, e.g., terminate the RCP operation and decontamination process [13].

### 3.2.2 SGTR

The SGTR event could be initiated by a guillotine break of one SG Tube. As a result of such a tube break, the RCS coolant would leak into the secondary SG system. Therefore, the RCS pressure and PZR level would decrease rapidly, as shown in Fig. 8 and Fig. 9. Note that the required minimum RCP inlet pressure is 22 bar. As shown in Fig. 8, the PZR pressure would be decreased below the required pressure after 152 s following the SGTR and the RCPs will be tripped right after the event occurs. Therefore, it is recommended to equip the control logic for automatic diagnosis and trip the RCPs.

It is important to note that the depletion of the PZR (i.e., 0% pressurizer level) would indicate a void formation or surface exposure in the RCS interior. As shown in Fig. 10

and Fig. 11, the RCS circulating flow would be constantly decreased and turbulent flows would be maintained for 20,000 s. To avoid leakage of RCS coolant via tube breakage, the secondary side pressurization of SG could be considered as well.

## 4. Conclusions

The flow characteristics of the Kori-1 NPP for the chemical decontamination process were analyzed. A MARS model was developed and the RCS flow conditions at steady-state and transient conditions were investigated. While the RCP operation would provide a sufficient RCS circulating flow, it would require the heat removal provided by the RHRS, as well as a maintained pressure. The results of this study may be utilized to optimize the decontamination process of this plant and prepare the required operational procedures.

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