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Flow Characteristics Evaluation in Reactor Coolant System for Full System Decontamination of Kori-1 Nuclear Power Plant

고리1호기 계통제염을 위한 원자로냉각재내 유동 특성 평가

Hak Soo Kim and Cho-Rong Kim*
Korea Hydro & Nuclear Power Co., Central Research Institute, 70, 1312-gil, Yuseong-daero, Yuseong-gu, Daejeon, Republic of Korea

김학수, 김초롱*
한국수력원자력㈜ 중앙연구원, 대전광역시 유성구 유성대로1312번길 70

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The Kori-1 Nuclear Power Plant (NPP), WH 2-Loop Pressurized Water Reactor (PWR) operated for approximately 40 years in Korea, was permanently ceased on June 18, 2017. To reduce worker exposure to radiation by reducing the dose rate in the system before starting main decommissioning activities, the permanently ceased Kori-1 NPP will be subjected to full system decontamination. Generally, the range of system decontamination includes Reactor Pressure Vessels (RPV), Pressurizer (PZR), Steam Generators (SG), Chemical & Volume Control System (CVCS), Residual Heat Removal System (RHRS), and Reactor Coolant System (RCS) piping. In order to decontaminate these systems and equipment in an effective manner, it is necessary to evaluate the influence of the flow characteristics in the RCS during the decontamination period. There are various methods of providing circulating flow rate to the system decontamination. In this paper, the flow characteristics in Kori-1 NPP reactor coolant according to RHR pump operation were evaluated. The evaluation results showed that system decontamination using an RHR pump was not effective at decontamination due first to impurities deposited in piping and equipment, and second to the extreme flow unbalance in the RCS caused deposition of impurities.

Keywords: Kori-1 nuclear power plant, System decontamination, Range of system decontamination, RHR pump

*Corresponding Author.
Cho-Rong Kim, Korea Hydro & Nuclear Power Co., Central Research Institute, E-mail: chorong.kim@khnp.co.kr, Tel: +82-42-870-5742

ORCID

Hak Soo Kim	http://orcid.org/0000-0003-3183-0659	Cho-Rong Kim	http://orcid.org/0000-0002-6697-8226

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국내 가동원전 중 2-루프 가압경수로인 고리1호기는 약 40년 운전한 후, 2017년 6월 18일 영구정지되었다. 영구정지된 고리1호기는 주요 해체작업을 수행하기전에 계통내 선량률을 저감시켜 작업자피폭을 최소화하기 위한 계통제염을 수행할 예정이다. 일반적으로, 계통제염 범위는 원자로압력용기, 가압기, 증기발생기, 화학 및 체적제어계통, 잔열제거계통 및 원자로냉각재계통 주요배관을 포함한다. 이러한 계통 및 기기 등을 효율적으로 제염하기 위해서는 제염과정에서 원자로냉각재계통내 유동특성을 평가할 필요가 있다. 계통제염을 위해 순환유량을 제공하는 방법은 다양하나, 본 논문에서는 잔열제거펌프 운전에 따른 고리1호기 원자로냉각재계통내 유동특성을 평가하였다. 잔열제거펌프를 이용한 계통제염은 원자로냉각재 내 유량의 불균형을 초래하여 계통내 기기 및 배관 등에 불순물을 침적시켜 제염이 효율적이지 않다는 것으로 평가되었다.

중심단어: 고리1호기, 계통제염, 계통제염범위, 잔열제거펌프

1. Introduction

System decontamination applied after nuclear power plants are permanently ceased is the technology to remove contaminated metal oxide films, or metal oxide deposits from the interior surfaces of systems or equipment such as RPV, SG, PZR, pipes, pumps, valves and heat exchangers, etc.. This technology is known to have a close relation to the decontamination effect of the circulation flow formed in RCS [1]. There are various methods of providing circulating flow rate to the system decontamination. Generally, the circulation flow rate is supplied by the reactor coolant pump, the residual heat removal pump, and vendor's pump as shown in Table 1 [2, 3]. The pumps to provide the circulation flow rate are selected according to the system decontamination scope.

The decontamination scope of Maine Yankee NPP was the full system excluded RPV and SG [2] as shown in Table 1. For Maine Yankee system decontamination, it was not possible to remove the contaminated materials of the entire planned decontamination scope with the vendor's pump (300~650 gpm) even if excluded RPV and SG. So, Maine Yankee NPP classified the decontamination scope to effectively decontaminate the contaminated system or equipment and conducted the system decontamination in first and secondary.

The decontamination scope of Connecticut Yankee NPP was similar with Maine Yankee NPP but only excluded RPV, and the RHR pumps were used to supply the chemical agents and the circulation flow rate [2]. Connecticut Yankee NPP was able to conduct the decontamination operation by single flow path using RHR pump (~2,000 gpm) with large capacity than Maine Yankee NPP.

Unlike Maine Yankee and Connecticut Yankee NPP,

Table 1. Comparison of system decontamination operation in NPP decommissioning

NPPs	Maine Yankee	Connecticut Yankee	Jose Cabrera
Decontamination Technology	DfD	HP CORD	DfD
Decontamination Scope	RCS, PZR, CVCS, RHRS (Exclude RPV & SG)	RCS, PZR, CVCS, SG, RHRS (Exclude RPV)	RCS, PZR, CVCS, RHRS, RPV, SG
Driving Force for Circulating Flow Rate	Vendor's Pump	RHRS Pump	RCP
Protection of RCP Seal	Isolation	Isolation	Supply DI Water

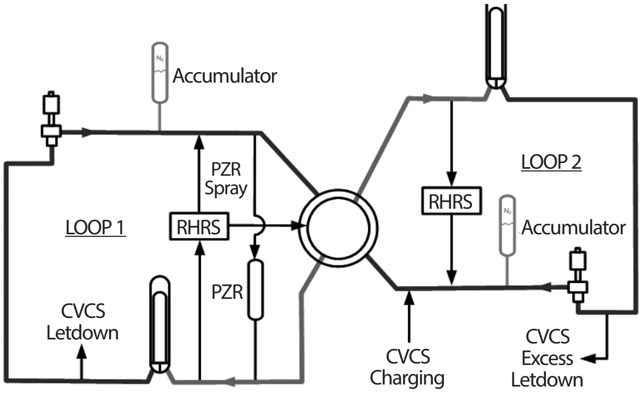

Fig. 1. Schematic diagram of WH 2-Loop PWR reactor coolant system.

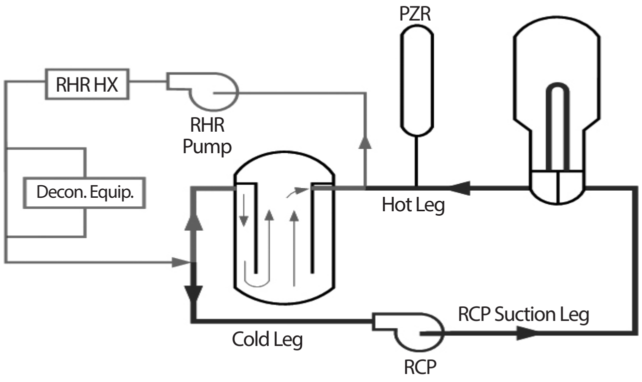

Fig. 2. Circulation flow in reactor coolant system with residual heat removal pump operation.

Table 2. Pressure drop in reactor coolant system under normal operation

Equipment or Piping	Pressure Drop (ΔP), [psi]
Reactor Pressure Vessel	41
Steam Generator	41
Hot Leg Piping	1.4
RCP Suction Piping	3.4
Cold Leg Piping	3.4

Jose Cabrera NPP included RPV and SG in the decontamination scope [3]. Jose Cabrera NPP used to the RCPs to supply the chemical agents and circulation flow rate in the decontamination scope. In this plant, nitrogen was pressurized in the PZR to provide the minimum pressure (~430 psig) required for RCP operation and the design was changed so that the demineralized water could be supplied separately to protect the RCP seals.

In this paper, the flow characteristics in Kori-1 NPP reactor coolant according to RHR pump operation were evaluated. In order to evaluate the flow characteristics, RCS, CVCS, RHRS, Safety Injection System (SIS) and piping were considered as the range of system decontamination.

2. Flow characteristics in reactor coolant system

It is essential that inner circulation flowrate be required for system decontamination operation and if the RCP is not operated, another pump should be used to supply the circulating flow. In this paper, the flow characteristics are evaluated based on the operation of RHR pump. Fig. 1 shows a schematic diagram of the WH 2-Loop PWR RCS [4], and Fig. 2 shows the circulation flow for operating RHR pump.

As shown in Fig. 2, the circulation flow in RCS with RHR pump operation is run into the RHRS from the hot leg for each loop which passes through the RHR pump, and then flows into the cold leg. Table 2 delineates the pressure drop characteristics in RCS during normal operation. The values shown in Table 2 are based on Kori-3&4 NPP, WH 3-Loop PWR, data because there is no Kori-1 NPP data available [5].

The pressure drop characteristics shown in Table 2 are the values of the conditions under which the RCP is operated and the fuel is present in the core. In system decontamination, the pressure drop formed in RPV is formed to be very low compared with the case in which the fuel is present. Even if two RHR pumps are operated, flow rates of up to 4,000 gpm (2,000 gpm / pump × 2 pumps) are only possible, and the pressure drop formed in RPV is less than 0.1 psi even under fuel conditions. Therefore, it can be

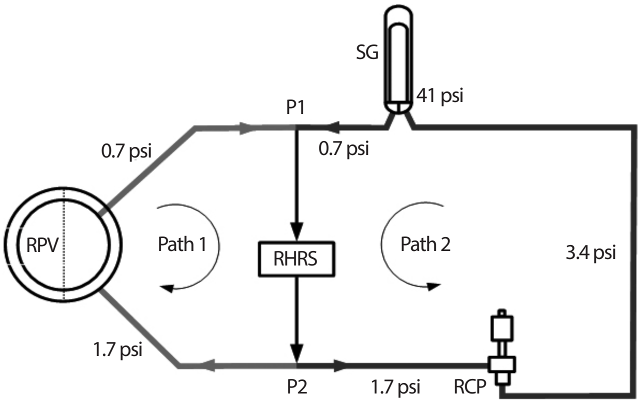

Fig. 3. Pressure drop and flow schematic in reactor coolant system with RHR pump operation.

assumed that there is no pressure drop through the RPV in case of system decontamination using the RHR pump since it is a negligible value in the fuel withdrawn condition. In addition, it is assumed that the pressure drop in the hot and cold legs is distributed by 50% based on the connection point with RHRS. Fig. 3 shows the flow path formed in the RCS when the RHR pump is used as the driving force of the circulating flow.

In Fig. 3, the branch points P1 and P2 have arbitrary pressure values, and the pressure drop ($\Delta P1$) through flow path 1 and the pressure drop ($\Delta P2$) through flow path 2 are assumed the same during RHR pump operation. That is, $\Delta P1 = \Delta P2$, and ΔP is proportional to KQ^2, so that it can be expressed as follows.

$$K1 \cdot Q1^2 = K2 \cdot Q2^2 \tag{1}$$

$$K1/K2 = Q2^2/\, Q1^2 \rightarrow \sqrt{K1/K2} = Q2/Q1 \tag{2}$$

where K is resistance coefficient and Q is flow rate (89,000 gpm).

The pressure drop for each path is calculated as follows.

$$\Delta P1 = 0.7 + 1.7 = 2.4 \text{ psi}$$
$$\Delta P2 = 0.7 + 41 + 3.4 + 1.7 = 46.8 \text{ psi}$$

$$\Delta P1 = K1 \times Q1^2, \quad K1 = \Delta P1/\, Q1^2 = 3.03 \times 10^{-10}$$
$$\Delta P2 = K2 \times Q2^2, \quad K2 = \Delta P2/\, Q2^2 = 5.91 \times 10^{-9}$$
$$\sqrt{K1/K2} = Q2/Q1 = 0.22645,$$

$$Q2 = Q1 \times 0.22645$$

The flow rates of Q1 and Q2 are 1,630 gpm and 370 gpm, respectively. In case of no fuel in the core, 1,630 gpm of 81.5% of the 2,000 gpm RHR pump flow is formed through the flow path 1, and the flow path 2 is formed of the flow rate of 370 gpm of 18.5%.

2.1 Flow Characteristic of Flow Path 1

As shown in Fig. 3, the flow path 1 is formed as RHRS → Cold Leg part → RPV → Hot Leg part → RHRS and it was estimated that a flow rate of 1,630 gpm, which is 81.5% of the RHR pump flow rate of 2,000 gpm, was formed. Table 3 is on the flow characteristics at flow path 1.

In order to prevent impurity deposit in the system piping, the flow velocity inside the piping is generally designed to be more than 2 $ft \cdot s^{-1}$ (0.6 $m \cdot s^{-1}$). Such a flow velocity is a value considering complex shapes such as vertical piping,

Table 3. Flow characterization of Flow Path 1

Equipment or Piping	Flow Velocity at RHR Pump (@1,630 gpm), [$ft \cdot s^{-1}$]	Reynolds No. @95℃
Cold Leg Piping	0.881	6.01×10^5
Hot Leg Piping	0.792	5.70×10^5
RPV	0.076	2.50×10^5

Table 4. Flow characterization of Flow Path 2

Equipment or Piping	Flow Velocity at RHR Pump (@370 gpm), $[ft\cdot s^{-1}]$	Reynolds No. @95℃
Cold Leg Piping	0.200	1.35×10^5
Hot Leg Piping	0.180	1.29×10^5
RCP Suction Piping	0.157	1.21×10^5
SG Tube	0.070	1.14×10^3

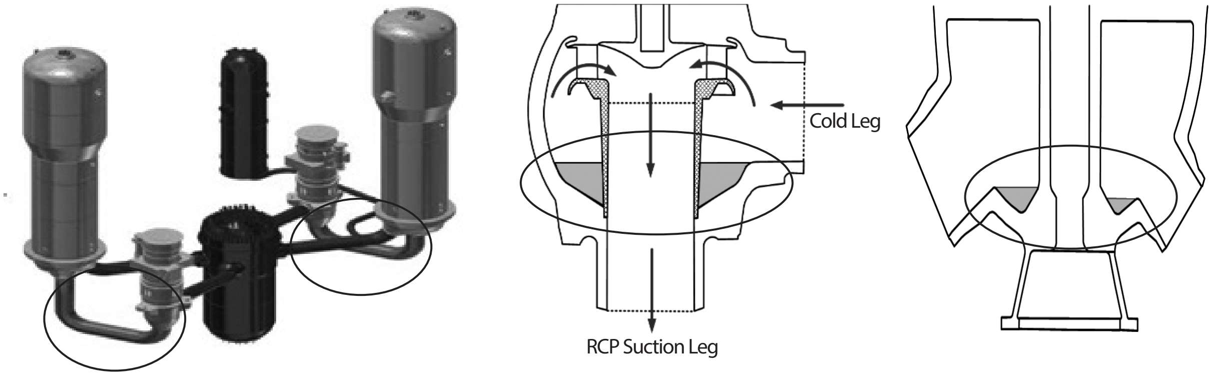

Fig. 4. Impurity deposit area in range of system decontamination.

Table 5. Volume of equipment and piping in Path 2

Equipment and Piping	Volume $[ft^3]$	Note
Cold Leg Piping	22.7	Assumed 1/2 of total cold leg
Hot Leg Piping	30.3	Assumed 1/2 of total hot leg
RCP Suction Piping	62.4	
SG/each (Primary side)	1,292.6	

valves and orifices. In case of horizontal piping, it is considered that impurities are not likely to be deposited in the flow velocity condition in Table 3, but it could not excludes the possibility that the impurities are deposited in the lower RPV region because the flow rate of RPV has a very low.

2.2 Flow Characteristic of Flow Path 2

Flow path 2 is circulated as RHRS → Cold Leg part → RCP Suction Leg → SG → Hot Leg part → RHRS and the flow rate of 370 gpm is formed, which is 18.5% of RHR pump flow rate. Table 4 shows the flow characteristics at flow path 2. The flow rate formed in the flow path 2 is about 370 gpm, which is considered to be a very low flow rate considering the piping size. If the flow rate through the system piping is low, there is a high possibility that impurities are deposited in the region that is structurally capable of forming a trap or below the U-shaped piping. As shown in Fig. 4, the areas where impurities may be deposited in the flow path 2 include the RCP suction U-shaped pipe, the SG chamber bottom area, and the RCP. Table 5 shows the volume of piping and equipment located at flow path 2 [1]. The

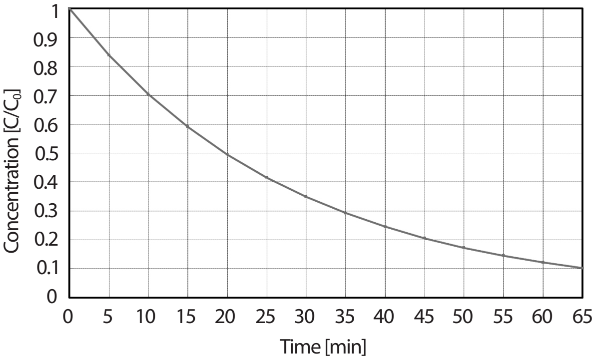

Fig. 5. Concentration change with time in flow path 2.

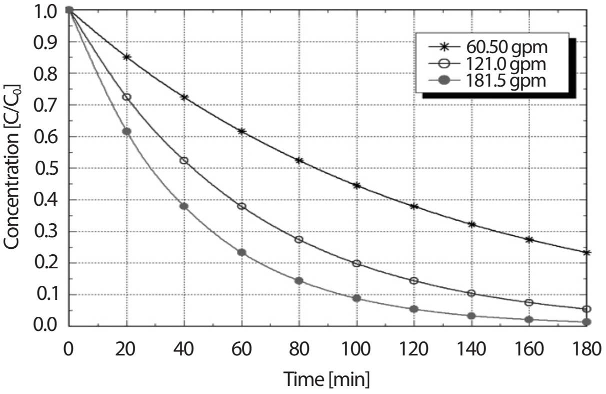

Fig. 6. Decontamination characteristics of PZR with auxiliary spray flow rate.

concentration change of the fluid in the system due to the feed and bleed is shown in Eq. (3).

$$C(t) = C_0\exp(-\alpha t) \quad (3)$$

where α is a ration of flow and volume.

Fig. 5 is shown the evaluation results of the decontamination performance of flow path 2 using Eq. (3). As shown in Fig. 5, it was estimated that it took 65 minutes to reduce the initial impurity concentration to 10% or less. However, since the Eq. (3) is derived from the assumption that all the fluids in the system are uniformly mixed at each time step, the concentration changes over time when the homogeneous mixing is not formed due to low circulation is shown in Fig. 5, and it is expected to take more time.

2.3 Decontamination Characteristics of PZR

If the RCP is not running, the main spray flow rate is not formed and the separate piping must be connected to use the auxiliary spray flow rate to inject the chemicals or decontamination the PZR, or to pass a part of RHR pump flow rate through the PZR. The flow rate of auxiliary spray is supplied by charging pumps in CVCS and the charging pump is reciprocating pump and installed 3 pumps in CVCS. The design flow rate of each pump is 60.5 gpm. The internal decontamination characteristics of the PZR are related to the flow rate through the PZR and can be evaluated using Eq. (3). According to Eq. (3), it was evaluated that the residual concentration of impurities in the PZR with the charging pump operation for supplying the auxiliary spray flow rate was 61.6% of the initial concentration after 60 minute, 37.9% for two charging pumps operation and 23.3% for three charging pumps operation, respectively. Fig. 6 showed the decontamination characteristics of the PZR with auxiliary spray flow rate.

2.4 Flow Distribution of Path 1 and 2 According to Flow Resistant Installation

When system decontamination is performed with only the RHR pump, there is an unbalance in the circulating flow rates of the flow path 1 and 2. In order to solve this unbalanced circulation flow, a separate facility is required, and a method of adding a facility (spider) for connecting a pipe to the inside of the RPV or a method of adding a flow-limiting resistor to the RPV can be considered [2]. When equipment are added to distribute the RHR pump flow rate equally, it is possible to distribute a flow rate of about 1,000 gpm. Table 6 shows the flow characteristics for the case where the flow resistors are added to the core area to change the flow rates of both flow path 1 and 2 to 1,000 gpm.

As we shown in Table 6, even if the flow rate of the RCP suction leg increases, it is still considered to be a low flow rate.

Table 6. Flow characterization for Flow Path 1 & 2 with 1,000 gpm

Equipment or Piping	Flow Velocity at RHR Pump (@1,000 gpm), [$ft\cdot s^{-1}$]		Reynolds No. @95℃	
	Path 1	Path 2	Path 1	Path 2
Cold Leg Piping	0.540		3.69×10^5	
Hot Leg Piping	0.486		3.50×10^5	
RPV	0.047	N/A	1.54×10^5	N/A
RCP suction Piping	N/A*	0.425	N/A	3.27×10^5
SG tube	N/A	0.188	N/A	3.09×10^3

* N/A: Not Applicable

As the flow rate of the flow path 2 increases, the flow rate of the flow path 1 decreases and the flow rate at the RPV also decreases. Therefore, the possibility of accumulating impurities at the bottom of the RPV will be relatively high. Fig. 7 shows the impurity concentration change with time of the fluid in the flow path 2 at a circulating flow rate of 1,000 gpm. It took 25 minutes for the circulation flow rate of 1,000 gpm.

3. Conclusion

This paper dealt with the flow characteristics in Kori-1 NPP reactor coolant according to RHR pump operation. It was demonstrated that sufficient circulation flow rate was required in the RCS to efficiently decontaminate systems and equipment, and the decontamination effect was improved as the circulation flow rate was increased. This paper showed that system decontamination using RHR pump could not be effective due to impurities deposited in piping and equipment, and the extreme flow unbalance in RCS caused the deposition of impurities as well. A separate facility can be considered to distribute the flow rate equally to solve the unbalance of the flow rate. But since the circulating flow is formed only by the RHR pump, the flow rate unbalance is still generated. As a result, it was confirmed that the use of the RHR pump as the driving force of the circulating flow was very limited.

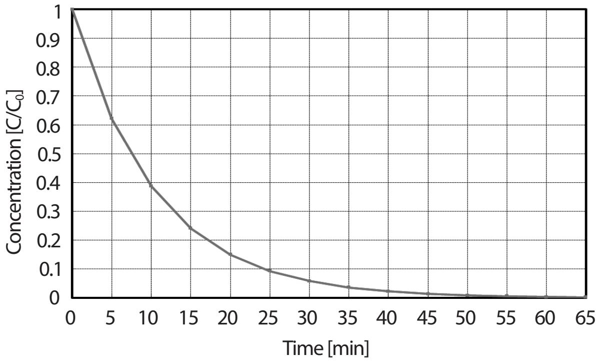

Fig. 7. Concentration change with time in flow path 1.

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