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Technical Note

Evaluation of system design modifications for full system decontamination of Kori Unit 1

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ABSTRACT

Kori Unit 1 is planning a system decontamination project to reduce radiation exposure of decommissioning workers, prevent the spread of contamination and down-grade the level of classification of radioactive waste. The system decontamination range for Kori Unit 1 will be the entire primary system, including RCS, CVCS and RHRS. Some system design modifications are required for the system decontamination operation. In this paper, major system design modifications were evaluated based on the conditions that system restoration is needed after completion of system decontamination. The major system design modifications are CIDF connection location to system, system decontamination operating pressure control, RCP seal water injection and formation of letdown flow. It was evaluated that there was no negative effect on the system due to the system design modifications. However, as the RCP seal water is injected into the system in the oxidation process, the concentration of the oxidizing agent is diluted. Therefore, the oxidizing agent injection and system decontamination operation procedures should be developed to address the dilution effect of the oxidizing agent. The system design modifications dealt in this paper will be finally confirmed through on-site investigation in the future, and if necessary, the system design modifications will be re-evaluated.

1. Introduction

System decontamination is a technology that uses chemical decontamination agents to remove the radioactive materials adhering to the inner surfaces of equipment and pipes in the primary system by maximizing the use of the existing system of the nuclear power plant (NPP) during 'transition period [1]' after a permanent shutdown of NPP. The benefits of system decontamination are that it can reduce radiation exposure of decommissioning workers, prevent the spread of contamination and down-grade the level of classification of radioactive waste [2].

In general, the system decontamination is performed by using a separate system decontamination facility or the NPP facility itself. KHNP and KEPCO E&C are currently performing the detailed design of CIDF (Chemical Injection and Decomposition&Treatment Facility), system decontamination commercial facility that can implement the CRI_RWDecom (Chemical Reagent Injection and RadWaste Decomposition&Treatment), a system decontamination technology developed by KHNP [3,4]. The main functions of CIDF are to inject chemicals (oxidizing and reducing agent) into the system to remove radioactive materials in the range of system decontamination, and to decompose and treat the generated decontamination waste. Recently, the system decontamination has been carried out by including the entire primary system in the range of system decontamination. For the Mihama Units 1&2, which performed the entire primary system decontamination using a system decontamination facility, the system design modifications were made for some systems required for system decontamination operation, including connection of a system decontamination facility [5]. KHNP is considering a project to decontaminate the entire primary system for the decommissioning of Kori Unit 1. The entire system decontamination of Kori Unit 1 is planned to be carried out using CIDF and some system design modifications will be made for system decontamination operation. This paper dealt with the system design modifications that should be considered for decontamination of the entire primary system of Kori Unit 1.

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2. System decontamination in permanently ceased commmercial nuclear power plants

According to the IAEA, as of 2021, 194 NPPs worldwide are permanently ceased [6]. In NPPs that were permanently ceased, system decontamination was performed to remove the radioactive materials in the system prior to major decommissioning activities, and various system decontamination technologies were developed and applied to decommission NPPs. The system decontamination technologies applied to the permanently ceased NPPs are CORD (Chemical Oxidation Reduction Decontamination) of Framatome, DfD (Decontamination for Decommissioning) of EPRI and ASDOC (Advanced System Decontamination by Oxidizing Chemistry) of Siempelkamp. Among these technologies, CORD and DfD use a separate system decontamination facility, and ASDOC uses the existing NPP system without a separate system decontamination facility. Table 1 shows cases of system decontamination operation for the decommissioning of NPPs.

3. Operation concept for performing Kori Unit 1 system decontamination

The system decontamination using a CIDF will be applied to the permanently ceased Kori Unit 1 for the first time in Korea. The system decontamination technology applied to Kori Unit 1 considers using CRI_RWDecom, which is an organic acid based chemical process, and system decontamination operation will be performed by connecting CIDF to the system. Table 2 shows the characteristics of CRI_RWDecom process with other technologies. Fig. 1 shows the schematic diagram of CIDF.

The operation concepts for Kori Unit 1 system decontamination are as follows [13,14].

- Utilization of plant facilities as much as possible
- System Decontamination Range: RCS (Reactor Coolant System), CVCS (Chemical and Volume Control System), RHRS (Residual Heat Removal System)
- Driving Force: RCP (Reactor Coolant Pump)
- Temperature and Pressure for System Decontamination Operation
  - Temperature: $<100\ ^\circ C$
  - Pressure: ~400 psig
- CIDF Connecting Location: RHRS
- CIDF Processing Capacity: 110 gpm

4. System design modifications for Kori Unit 1 system decontamination

Although the existing system is utilized as much as possible for the system decontamination operation, some system design modifications are required. The major system design modifications to be considered are as follows.

- CIDF connection location to system
- System decontamination operating pressure control
- Reactor coolant pump seal water injection
- Formation of letdown flow

System design modifications were evaluated based on methods that minimize modifications to the existing system and allow restoration to its original state after system decontamination.

4.1. CIDF connection location to system

Fig. 2 is a schematic diagram of the system connection of CIDF.

The flow path from the system to the CIDF is branched at the downstream of the heat exchanger in RHRS, and the flow path from the CIDF to the system is supplied to the upstream of the RHR pump. Fig. 3 shows the system connection location of the CIDF inlet pipe. The CIDF inlet pipe is connected to the blind flange located at the downstream of the VCS-9663 or the VCS-9664.

Fig. 4 shows the system diagram of the suction part of the RHR pump. The outlet pipe of the CIDF is connected to the spool piece or the temporary connection located at the downstream of VRH-9403A/B in the suction part of the RHR pump. As shown in Figs. 3 and 4, the method of connecting CIDF to the system was evaluated to have no negative effect on the system. Because the CIDF inlet/outlet piping is connected to the small branch piping in RHRS, there is no effect on the RHRS main piping and system operation. In addition, the CIDF operating flow rate of 110 gpm is much lower than the RHRS operating flow rate of 2000 gpm, so it is not expected to have an effect on the RHRS operating flow rate.

4.2. System decontamination operating pressure control

Although the system decontamination operating pressure is not a direct process variable for the system decontamination operation, it is necessary to maintain the system pressure in order to satisfy the NPSHR (Net Positive Suction Head Required) for RCP operation because the circulating flow rate within the range of system decontamination is formed using the RCP. The actual system decontamination operating pressure is determined by considering the characteristics of the RCP and the relief valve setpoint for LTOP (Low Temperature Over pressurization Protection). The operating pressure of Kori Unit 1 system decontamination is assumed to be 400 psig.

In normal operation, the pressure of RCS is controlled using steam in upper part of the PZR (pressurizer), whereas the operating pressure in system decontamination must be controlled by solid operation or filling non-condensable gas in other equipment because the steam cannot be used in system decontamination

Table 1
Cases of system decontamination operation.

Nuclear Power Plant	Maine Yankee [7]	Connecticut Yankee [7]	Jose Cabrera [8]	Mihama [5]
System Decontamination Technology	DfD	CORD	DfD	HP CORD UV
Decontamination Range	RCS/PZR/CVCS/RHRS (RPV/SG bypass)	RCS/PZR/CVCS/RHRS (RPV bypass)	RCS/PZR/CVCS/RHRS	RCS/PZR/CVCS/RHRS
Driving Force	Vendor's pump	RHR pump	RCP	RCP
Operation Temp./Pressure	$195 \pm 10^\circ$/N/A[a]	$195 \pm 10^\circ$/N/A	200°/430 psig	200–260°/~430 psig
Temp. Control	Vendor's Equipment	PZR Heater	RCP, RHR Hx	RCP, RHR Hx
Pressure Control	N/A	N/A	PZR N_2 Charge	Accumulator N_2 Charge
RCP Seal Protection	Isolation	Isolation	DI Water Injection[b]	DI Water Injection[b]
Charging Pump	Bypass	Bypass	In-Service	In-Service

[a] Not available.
[b] Applicable only in oxidation process.

Table 2
Characteristics comparison of CRI_RWDecom and competitive technologies [9–12].

Process	CRI_RWDecom	HP CORD UV	DfD	ASDOC_D-MOD
Oxidizing Agent (Concentration)	$HMnO_4$ (200 ppm)	$HMnO_4$ (300 ppm)	$KMnO_4$ (200 ppm)	$HMnO_4$ (50 ppm)
pH Adjuster (Concentration)	HNO_3 (Equiv. to $HMnO_4$)	N/A[a]	HBF_4 (10 mM)	Methane sulfonic acid (<100 ppm)
Reducing Agent (Concentration)	$H_2C_2O_4$ (2000 ppm)	$H_2C_2O_4$ (2000 ppm)	$H_2C_2O_4$ (Equiv. to the residual $KMnO_4$)	$H_2C_2O_4$ (100 ppm)
Treatment and Decomposition	UVC and Ion Exchanger in Facility	UVB and Ion Exchanger in Facility	Ion Exchanger in Facility	Ion Exchanger in Plant

[a] Not applicable.

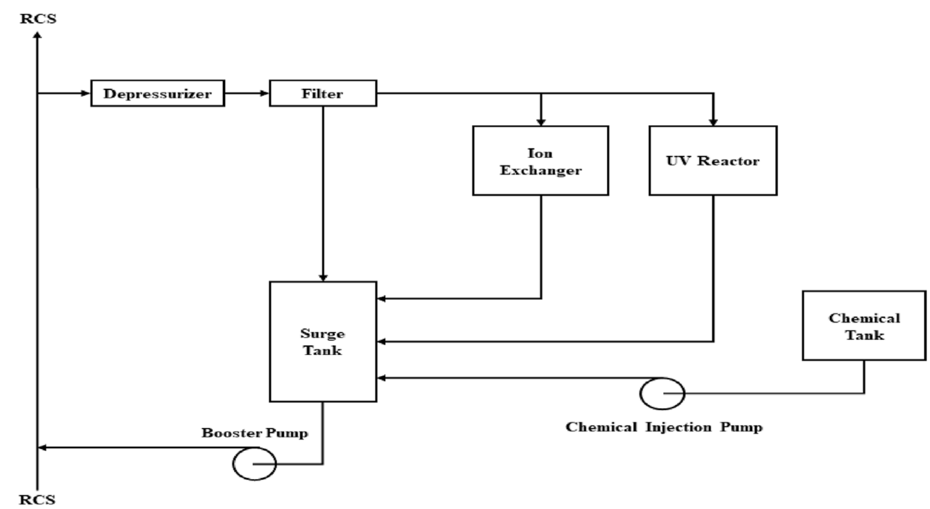

Fig. 1. Schematic diagram of CIDF

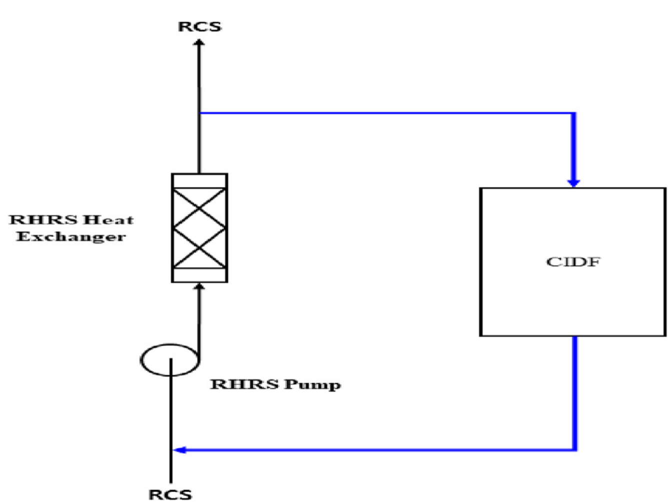

Fig. 2. Schematic diagram of system connection of CIDF

operation. As shown in Table 1, it can be seen that the operating pressure in the system decontamination is controlled by filling the upper part of PZR or Accumulator with non-condensable gas. NPPs use nitrogen or air as a non-condensable gas. The compressed air used in NPPs is divided into instrument and service. The compressed air used in Kori Unit 1 does not exceed 150 psig. As a result, an additional separate compressor is required to supply compressed air over 400 psig. Nitrogen supply to Kori Unit 1 uses the liquid nitrogen common facility installed in Kori Unit 2 or a high pressure nitrogen manifold. Fig. 5 is a schematic diagram of the nitrogen supply system for Kori Unit 1. The nitrogen supply system of Kori Unit 1 can supply low and high pressure nitrogen to the system, and it was confirmed that the high pressure nitrogen manifold can provide a pressure of 400 psig or more to Accumulator as shown in Fig. 5. Methods for controlled the system decontamination operating pressure using the nitrogen supply system were reviewed.

4.2.1. *Pressure control by Pressurizer*

There is no nitrogen supply pipe connected to the PZR. An additional pipe connection is required to supply nitrogen to the upper part of the PZR.

Fig. 6 shows a part of the upper system diagram of the PZR. The spray pipe, the pressurizer safety valves and the depressurizer system are connected to the upper part of the PZR and these should be used for pressure control. As shown in Fig. 6, it was evaluated that the pressure could be controlled by connecting the inlet pressure relief valve to the blind flange located at the downstream of the VRC-902 and the outlet pressure relief valve to the blind flange located at the downstream of the VRC-8093. The schematic diagram of pressure control using a PZR is shown in Fig. 7.

The method of controlling the system decontamination operating pressure using the PZR does not has a negative effect on system operation and related systems. However, since the upper part of the PZR included in system decontamination range is filled with nitrogen gas, there is a disadvantage that the upper part of the PZR is not decontaminated. On the other hand, the pressure control method using a PZR has the advantage that it can be operated in a certain water level range using the PLCS (Pressurizer Level Control System).

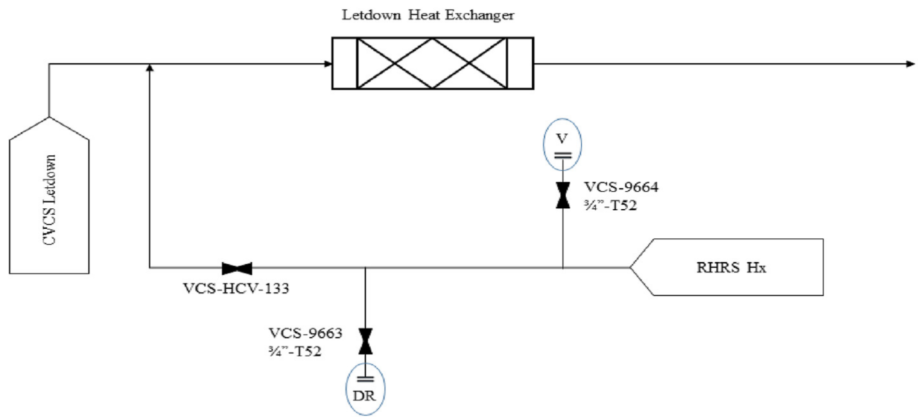

Fig. 3. System connection location of the CIDF inlet pipe.

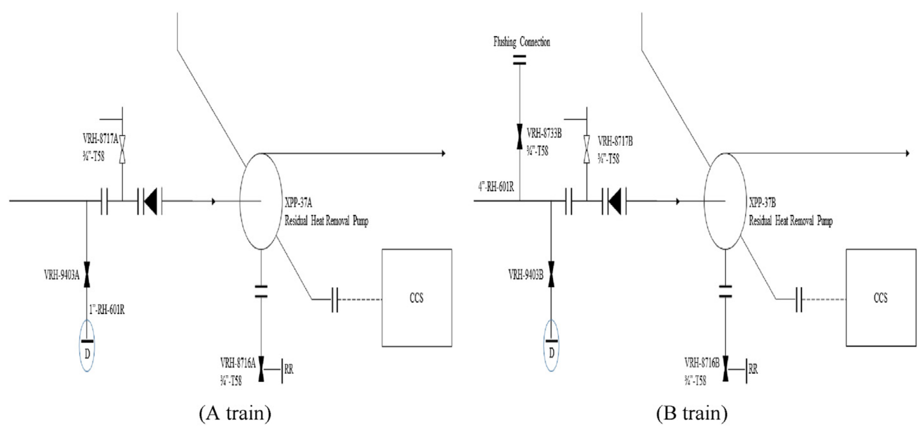

Fig. 4. System connection location of the CIDF outlet pipe.

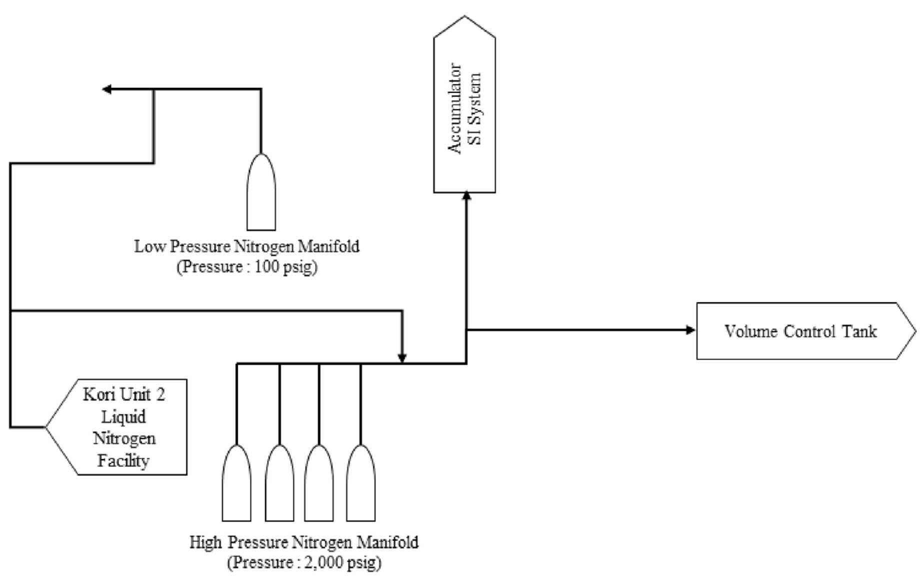

Fig. 5. Schematic diagram of Nitrogen Supply System.

4.2.2. Pressure control by Accumulator

Fig. 8 is a schematic diagram of the system connected to the upper part of Accumulator. A pipe that can supply nitrogen at a pressure of 400 psig or more is connected to the upper part of Accumulator, so a separate pipe connection for nitrogen supply is not required. However, since the pressure of nitrogen supplied to Accumulator is higher than the operating pressure of the system decontamination, it is necessary to install a pressure control valve

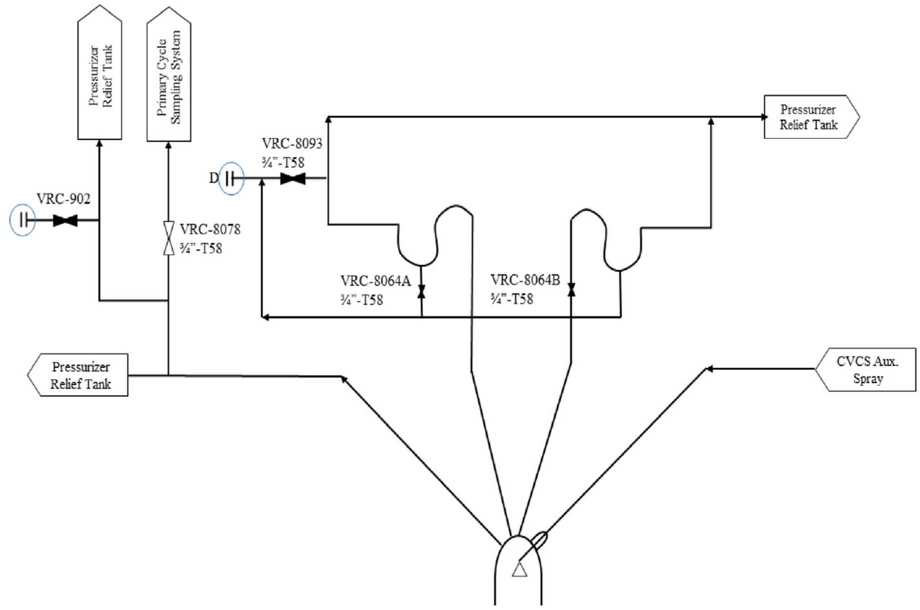

Fig. 6. Upper system diagram of Pressurizer.

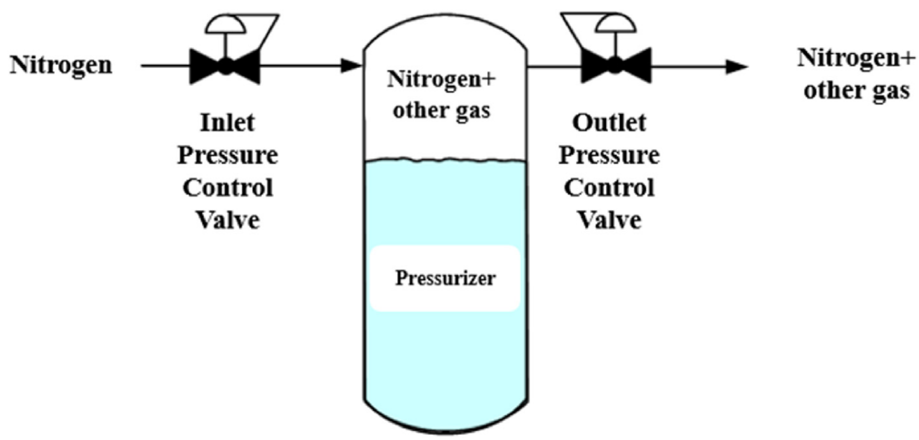

Fig. 7. Schematic diagram of pressure control using Pressurizer.

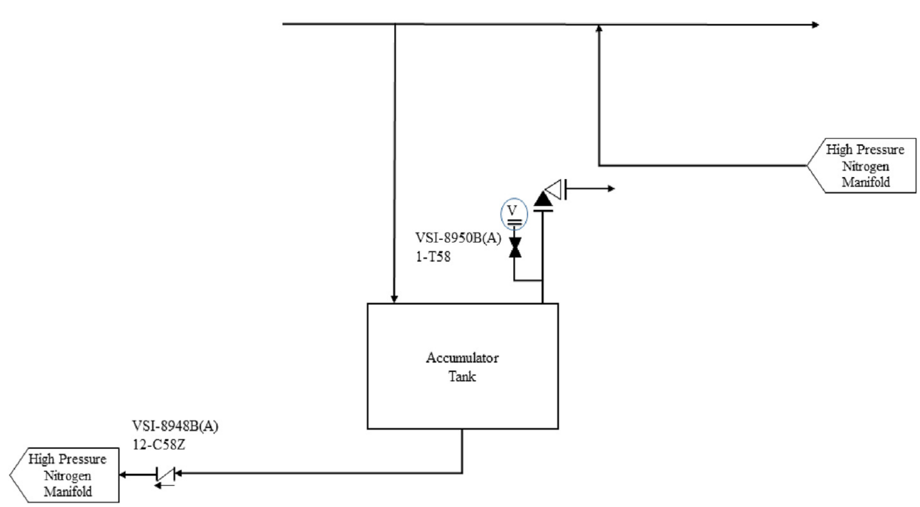

Fig. 8. Upper system diagram of Accumulator.

that can reduce the pressure to the operating pressure of the system decontamination. The pressure control valve is installed on the blind flange located at the downstream of the VSI–8950B/A to control the pressure.

The method of controlling the pressure by filling Accumulator with nitrogen has the advantage of decontaminating the entire PZR. On the other hand, nitrogen flows into or out of Accumulator according to the change of the fluid within the system decontamination range. In this case, there may be a difference between the composition of the fluid in Accumulator and within the range of system decontamination, which may affect the system decontamination process. Therefore, it is necessary to establish a system decontamination operation procedure taking into the above account. In addition, pressure control using Accumulator does not have an equipment to automatically control the water level in Accumulator, so the operator has to manually adjust the water level or add a separate automatic water level control equipment. It is necessary to remove the internal components of the check valve to form a bidirectional flow path since a check valve is installed in the pipe connected from Accumulator to RCS.

4.3. Reactor Coolant Pump seal water injection

RSSS (RCP Seal Supply System) is an equipment for injecting seal water (Demineralized water) into RCP during the system decontamination oxidation process. It is known that the oxidizing agent and reaction by-products used in the oxidation process have a negative effect on the RCP seal [14,15]. Therefore, a separate RSSS is required during the oxidation process to protect the RCP seal. RSSS receives demineralized water from the demineralized water supply system and supplies RCP seal water to RCP through the CVCS in shown in Fig. 9.

Fig. 10 is CVCS seal water supply system. It is desirable to connect the RSSS to the upstream of the Seal Water Injection Filter and evaluated that RCP seal injection operation in oxidation process should be performed by connecting it to the blind flange located at the downstream of the VCS-9680.

During the oxidation process, the RCP seal water flowing into the system decontamination range results in dilution of the oxidizing agent. The dilution effect of the concentration of the oxidizing agent in the oxidation process should be considered as the RCP seal water is injected into the system decontamination range. Kori Unit 1 has two RCPs, and a seal water injection flow rate of 8 gpm is supplied to each RCP. At the normal operating pressure, 3 gpm of the 8 gpm seal water injection flow rate is recovered to the VCT (Volume Control Tank) in CVCS, but at the system decontamination operating pressure, the recovered flow rate to the VCT was expected to be insignificant, so it is assumed that all 8 gpm is injected into the system decontamination range. The dilution effect of the oxidizing agent in the system decontamination process of Kori Unit 1 was evaluated with reference to Mihama Unit 1. The system decontamination of Mihama Unit 1 was completed by performing 3 cycles (one cycle is consists of oxidation, reduction, decomposition and purification processes) and the oxidation process took an average 1.2 days per cycle, and a total of 3.7 days until the system decontamination was completed [5]. During the oxidation process of Kori Unit 1, RCP seal water will enter into the system by 13,824 gallons per cycle and 42,624 gallons by the completion of the system decontamination. Therefore, since the Kori Unit 1 system decontamination considers the operation of two RCPs, the RCP seal water entering the system will be 27,648 gallons per cycle and a total of 85,248 gallons during the system decontamination operation. Assuming that the total volume within the system decontamination range of Kori Unit 1 is 57,600 gallons (7700 ft^3) [14], the concentration of the oxidizing agent after 1.2 days of the oxidation process is diluted to about 62% of the initial concentration even without considering the oxidizing agent consumed by the reaction. Therefore, the oxidizing agent injection and system decontamination operation procedures should be established in consideration of the oxidizing agent dilution effect. If the volume, pressure and temperature of the fluid within the system decontamination range are constant during the oxidation process, 27,648 gallons of fluid should be discharged out of the system decontamination range every cycle. Kori Unit 1 has two Holdup Tanks with a capacity of 52,500 gallons and can accommodate all of the fluid discharged out of the system decontamination range during the oxidation process. Therefore, it was confirmed that the volume change due to the seal water injected into the system during the oxidation process can be sufficiently accommodated with Holdup Tanks.

4.4. Formation of letdown flow

CVCS in the system decontamination range is used to control the volume of fluid within the system decontamination range during system decontamination operation. For this, CVCS should be able to provide a sufficient letdown flow rate. Fig. 11 shows the CVCS letdown system. As shown in Fig. 11, there is no pipe for bypass the letdown orifices, so it is impossible to provide sufficient letdown flow rate under the low system decontamination operating pressure. In the condition of the low RCS pressure during NPP operation, the desired letdown flow rate is formed through RHRS. However,

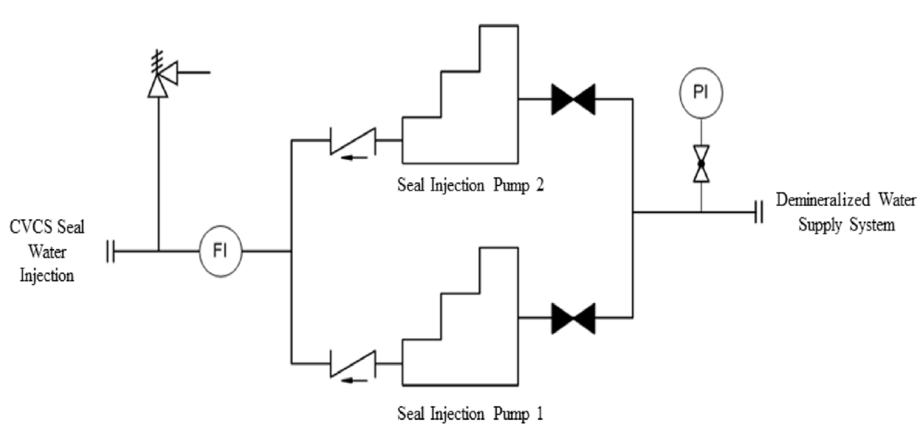

Fig. 9. Schematic diagram of RSSS

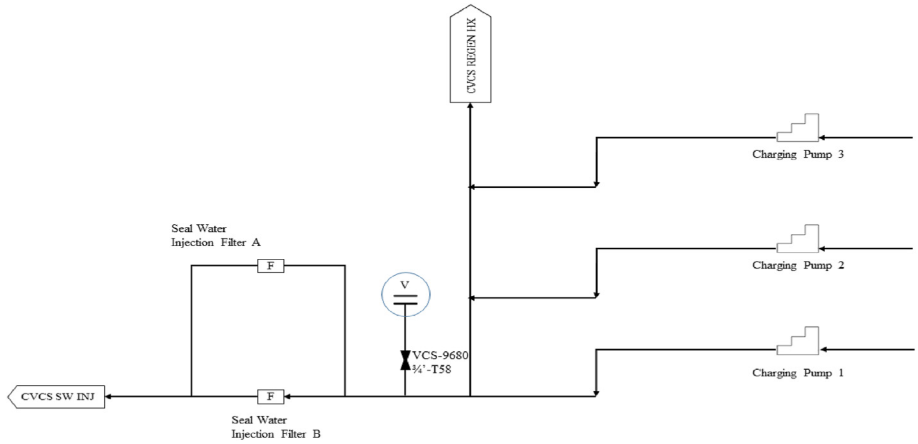

Fig. 10. CVCS Seal Water Supply System.

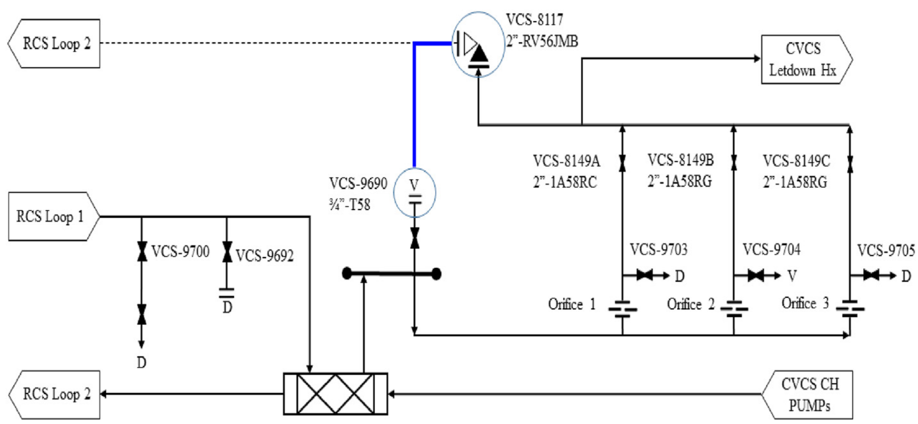

Fig. 11. CVCS Letdown System.

since the connecting pipe of the RHRS and CVCS Letdown system should be isolated for system decontamination operation, a new pipe that bypasses the letdown orifices is required to provide the sufficient letdown flow rate. Removal of the letdown orifices is also an option, but it is not considered because the orifices are welded to the pipe. Since all of the drain or vent pipes shown in Fig. 11 exist inside the Reactor Building, it is possible to connect the upstream and downstream of the letdown orifices using a high-pressure hose. There are VCS-9700, VCS-9692 and VCS-9690 where hose connections in upstream of the letdown orifice are possible. For the downstream of the letdown orifice, it is possible to connect to VCS-9703, VCS-9704, VCS-9705 and VCS-8117. The blue line shown in Fig. 11 was evaluated as the optimal connection point.

The design modification to connect a separate hose at the upstream and downstream of the letdown orifices to form the letdown flow rate was evaluated to have no negative impact on the system operation and the system decontamination process.

5. Conclusion

Kori Unit 1 is planning a system decontamination project to reduce radiation exposure of decommissioning workers, prevent the spread of contamination and down-grade the level of classification of radioactive waste. The range of system decontamination for Kori Unit 1 will be the entire primary system, including RCS, CVCS and RHRS. System decontamination operation is not accomplished only by connecting the system decontamination facility to system, which requires some system design modifications. In this paper, major system design modifications were evaluated based on the conditions that system restoration is needed after completion of system decontamination without destructive work such as cutting in consideration of licenses and permits related to decommissioning of NPP. The system design modifications for system decontamination of Kori Unit 1 were as follows, and it was evaluated that there was no negative effect on the system.

- CIDF connection location to system
- System decontamination operating pressure control
- Reactor coolant pump seal water injection
- Formation of letdown flow

However, in the oxidation process, it was evaluated that the concentration of the oxidizing agent was diluted to about 62% of the initial concentration by the seal water injected to protect the RCP seal. It was evaluated that the oxidizing agent injection and system decontamination operation procedures should be developed to address the dilution effect of the oxidizing agent. The system design modifications dealt with in this paper will be finally confirmed through on-site investigation in the future, and if necessary, the system design modifications will be re-evaluated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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