Reactor Vault Cooling System (RVCS) Effect on ULOHS Event for the Prototype Gen-IV SFR

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1. Introduction

Recently, a reactor vault cooling system (RVCS) for the prototype Gen-IV sodium-cooled fast reactor (PGSFR) is designed for a function of heat removal during a severe accident. The RVCS is a passive air cooling system located between containment concrete and vessel. The major goal for the RVCS is cooling internal structures in plant, such as a concrete and reactor vessel (RV). The RVCS was not considered in previous safety analysis for the PGSFR. The RVCS can have an influence on the reactor vessel temperature, which is a very important parameter in a RV expansion reactivity feedback during unprotected accident, especially unprotected loss of heat sink (ULOHS). Therefore, in order to study the RVCS effect on accident, the ULOHS event with RVCS is preliminarily analyzed with tentative design parameters.

2. RVCS Model in MARS-LMR

2.1 RVCS Description

Fig.1 shows a conceptual description for the RVCS in the PGSFR. There is no determined design values yet due to an under-design status. The RVCS is basically operated by a natural circulation. A cold air enters through two inlets and flows down the gap between an air separator (SP) outer wall and concrete inner wall. Then, air flow passes upward the gap between the air separator and containment vessel outer wall (CV).

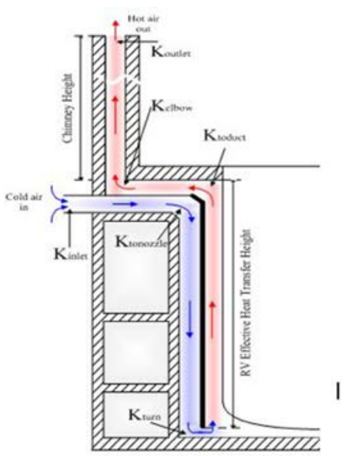

Fig. 1. Conceptual image for the RVCS in the PGSFR [1]

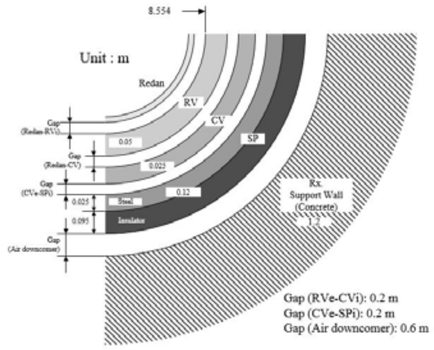

Fig. 2. Radial Structures in the PGSFR with RVCS [1]

During the pass through these two gaps, the air is heated. Finally, a hot air flow goes out to an ambient through the chimney connected to outlet region of the RVCS. Fig. 2 shows radial structures from hot pool to containment in the PGSFR. The hot pool and cold pool is separated by a redan structure. A reactor vessel (RV) is filled with cold pool sodium. There is a gap between the CV and RV, which is filled with N_2 gas. When the RV leak occurs, the sodium in the cold pool fills the gap and prevent additional leakage of the sodium. To make air flow passes in the RVCS, the SP is integrated between the CV and containment concrete (CC). The outer wall of the CV is made by an insulation material.

2.2 RVCS Model in MARS-LMR

Fluid team in the SFR design division calculated the RVCS performance to evaluate the heat balance of the PGSFR and proposed tentative design parameters for the RVCS [1]. All design parameters related to the RVCS are based on this report. To add the new RVCS model in the existing PGSFR model for MARS-LMR, an individual RVCS model is developed and tested. The previous model has the CV as last structure. Thus, the RVCS is modeled including the CC. The major heat transfer mechanisms in the RVCS can be convective and radiation heat transfers. Dittus-Boelter correlation (Eq. 1) is used for convective heat transfer [2].

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \qquad (1)$$

The radiation heat flux on the i-surface can be solved with following equation [3].

$$q_i'' = R_i - \sum_{j=1}^{n} R_j F_{ij} = \frac{\varepsilon_i}{\rho_i}\left(\sigma T_i^4 - R_i\right) \quad (2)$$

The R is radiosity. The ε and ρ indicate emissivity and reflectivity, respectively. The σ is Stefan-Boltzmann constant. F_{ij} indicates a view factor from i-surface to j-surface. To simplify evaluation of the view factor, only facing surfaces in the same elevation are considered. To obtain the heat flux on i-surface, the R_i can be solved with linear algebraic equation in MARS-LMR.

Fig. 3 shows RVCS nodalization for the MARS-LMR. The CV, SP, and CC are modeled as heat structures with tentative design values in Ref. 1. The inlet and outlet of the RVCS air flow are modeled with volume no. 40 and 75, respectively. To control the air flow, the damper in the inlet is modeled with valve component (no. 42). The gaps between the concrete, SP, CV, and RV are modeled with volume no. 50, 60, and 90, respectively. The chimney region is modeled with volume no. 70. The reactor vessel heat structure is connected cold and hot pool components, such as component number of 105, 100, 248, and 249. The concrete outer wall is considered as boundary with insulation condition. The input parameters for the RVCS model are summarized in Table I.

2.3 RVCS operational conditions

Design parameters and operational logic for the RVCS is necessary to evaluate the RVCS performance during the event. However, these information is not finalized yet. The heat loss during normal operation can be limited by 0.125% of the rated power, which is approximately 0.48 MW [1]. In addition, when the damper is fully opened during normal operation, the heat loss was 0.68 MW [1]. Thus, in this study, these heat losses are applied to tentative operational condition.

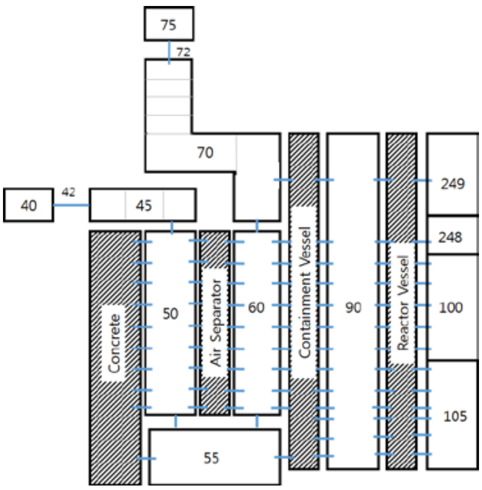

Fig. 3. RVCS Nodalization for MARS-LMR

Table I: Input Parameters in the RVCS Model†

	Thickness [m]	ε	Material
RV	0.05	0.4	SS316
CV	0.025	0.4	2-1/4 Cr-1Mo steel
SP	0.025 (inner)	0.4	steel
	0.095 (outer)	0.8	insulator
C	1.2	0.9	Concrete
	Gap [m]	F_{ij}	Fluid
RV/CV	0.2	0/1, 0.95/0.05	N_2
CV/SP	0.1	0/1, 0.97/0.03	Air
SP/C	0.6	0/1, 0.88/0.12	Air

† values and materials are tentatively determined based on Ref.1.

3. RVCS Performance Test

Before applying the RVCS model to entire PGSFR plant model, in order to evaluate the RVCS operational condition and performance, the RVCS is individually modeled from the RV heat structure, which treated with uniform and constant temperature condition on the inner wall surface. In this calculation, it is assumed that the damper is fully opened. Fig. 4 shows the RVCS heat loss for different air flow conditions applying the RVCS temperature of 390 °C. When the air flow is 4.96 kg/s, the heat loss is about 0.7 MW, which is assigned as heat loss condition with the opened damper in the normal operation condition. When the air flow increased to 122 %, the heat loss is increased to 32 %. In addition, the RVCS heat loss is calculated for different RV inner wall temperatures from 390 °C to 590 °C. . When the RV temperature rises from 390 °C to 590 °C, the air flow and the heat loss is increased to 65% and 166 %, respectively. As the RV temperature rises, the RVCS heat loss is drastically increased, although the air flow rate is relatively less increased. Therefore, this results indicates that the RV temperature has higher sensitivity on the RVCS heat loss.

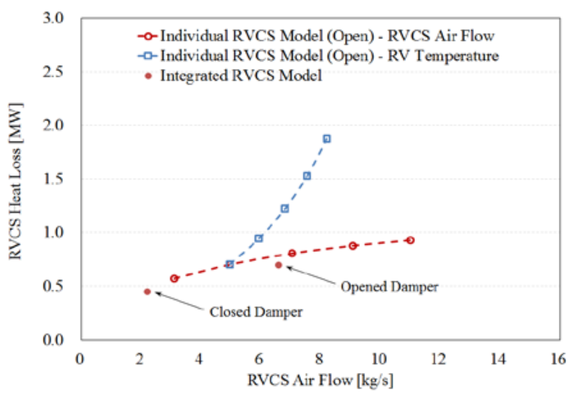

Fig. 4. RVCS Heat Loss in the Individual RVCS Model for Different Conditions

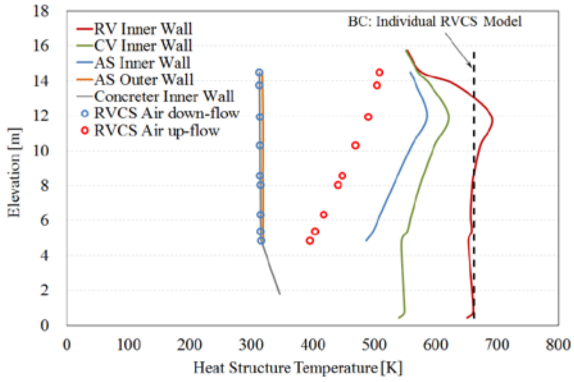

Fig. 5. Axial Temperature Distribution during Normal operation in the PGSFR

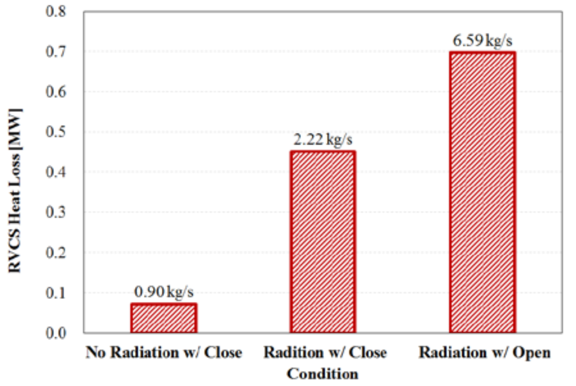

Fig. 6. RVCS Heat Loss in the Integrated RVCS Model for Different Conditions

Based on the RVCS test with the individual RVCS model, the RVCS model is integrated to the PGSFR whole systems, such as hot and cold pool, pumps, core, steam generator, decay heat removal system (DHRS), and so on. As shown in Fig. 4 actual RV temperature is slightly lower than that in the simple RVCS model, especially on the cover gas region (top). Therefore, to achieve the RVCS heat loss of 0.7 MW when the damper is opened, the air flow rate is increased comparing to the individual RVCS model. Moreover, to satisfy the heat loss of 0.48 MW when the damper is closed, the air flow rate is controlled with modeled valve. Fig. 6 shows the heat loss results for the integrated RVCS model. In addition, when the radiation heat transfer is ignored, the heat loss is reduced to 40%, which can be a reason for higher sensitivity of the structure temperature as shown in Fig. 4. In other words, major heat transfer mechanism is the radiation heat transfer between the heated surfaces. As shown in Fig. 5, the temperature change in the down flow of the gap between the CC and SP is negligible, however, the air temperature rises in the up flow of the gap between the SP and CV, which can be a driving force for the RVCS air flow.

4. RVCS Effect on ULOHS Event

The RVCS is newly considered system in the safety analysis for the PGSFR. The RVCS can be an additional heat removal component during accident condition, so the heat structure temperature can be decreased by higher heat removal capability. Especially, the RV is one of important structure for an expansion reactivity feedback. When the RV temperature rises, it should be expanded. Then, the control rod position in the active core becomes higher, which makes positive reactivity feedback. In order to study the RVCS effect on the unprotected events, the unprotected loss of heat sink (ULOHS) event is analyzed with and without RVCS. The RVCS model and input parameters are same to those in the performance test. The ULOHS event is initiated with feed-water isolation at initial 10 seconds. The DHRS is activated at 5 seconds after starting accident. When the RVCS damper is opened, the transient result is also compared. The delay time for the RVCS damper open is same to that in the DHRS.

Fig. 7 shows a peak clad temperature during the ULOHS event. When the RVCS damper is closed, the peak clad temperature is increased comparing with the without RVCS case. However, the opened RVCS damper shows lower peak clad temperatures. Generally, when the steam generator is tripped, the heat removal through the steam generator is failed. Thus, the cold pool temperature rises by when heat removal capability of the DHRS can cover the total reactor power. As the rector power is decreased by reactivity feedbacks, which is generated by temperature change in the fuel, coolant, and structures. The temperature difference between cold (core inlet) and hot (core outlet) pools is reduced, because primary pumps are still working as shown in Fig. 8. Thus, the inlet temperature rise is dominant during the ULOHS event, which means the thermal expansion of the RV, contacted to the cold pool, can be dominant. So, the CRDL/RV expansion reactivity becomes positive in the ULOHS event as shown in Fig. 9.

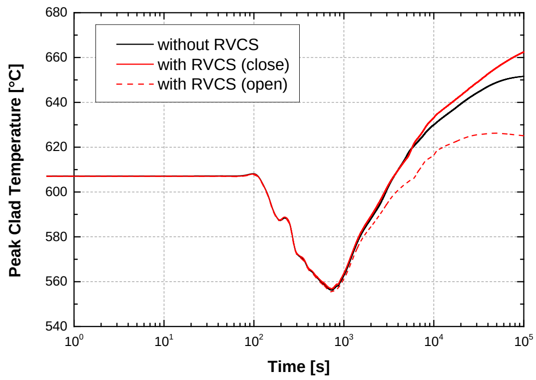

Fig. 7. Peak Coolant Temperatures during ULOHS Event for Different RVCS conditions

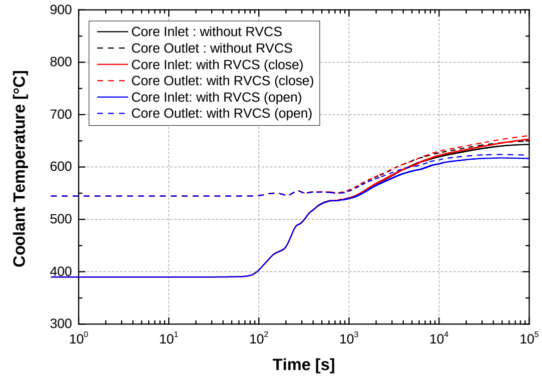

Fig. 8. Core Coolant Temperatures during ULOHS Event for Different RVCS conditions

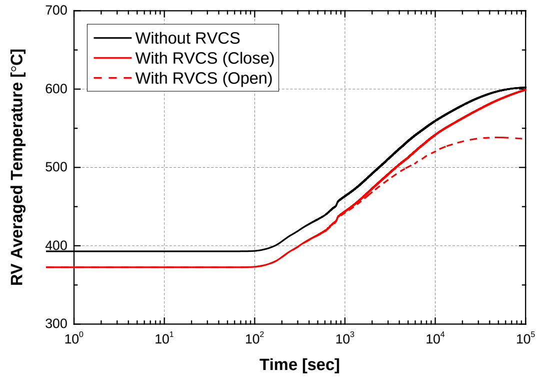

Fig. 10. RV Averaged Temperatures for Different RVCS conditions during ULOHS Event.

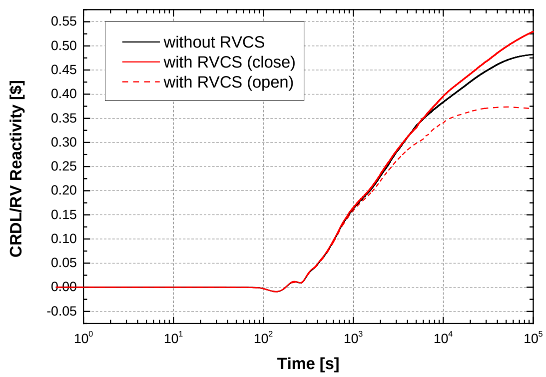

Fig. 9. CRDL/RV Expansion Reactivity Feedback during ULOHS Event for Different RVCS conditions

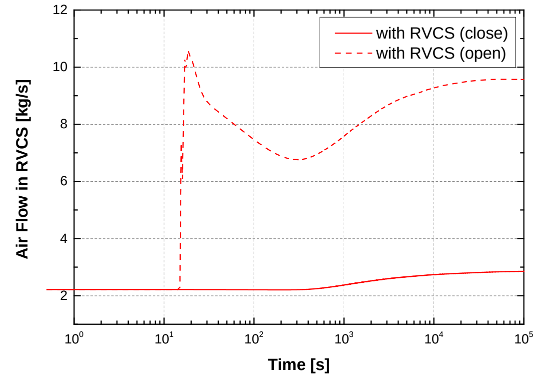

Fig. 11. Air Flow Rate in the RVCS for Damper Conditions during ULOHS Event.

Fig. 9 shows the CRDL/RV expansion reactivity feedback during ULOHS event with different RVCS conditions. When the RVCS damper is closed, the reactivity feedback is higher than that in the without RVCS case. However, when the RVCS damper is opened, the positive reactivity feedback is reduced due to lower thermal expansion of the RV. Fig. 10 shows averaged RV temperatures for different RVCS conditions. The RVCS model added the PGSFR model, the RV temperature rise is higher than that in the without RVCS case, which means higher thermal expansion of RV as shown in Fig. 9. When the RVCS damper is opened, the heat removal capability can be drastically increased as the cold pool temperature rises. Thus, the RV temperature in the opened damper case rise is smaller than that in the closed damper as shown in Fig. 10. Figure 11 and 12 show the air flow rate and heat loss during the ULOHS transient, respectively. When the RVCS damper is closed, the air flow rate is slightly increased to about 3 kg/s, and the heat loss is reached to 1.1 MW. When the RVCS damper is opened, the air flow is drastically increased to about 9.8 kg/s, and the heat loss is reached to 1.7 MW.

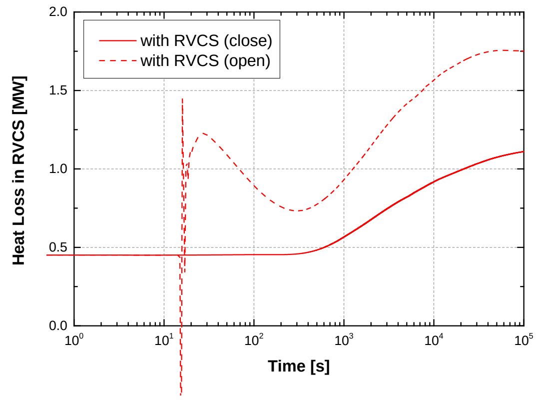

Fig. 12. Heat loss in the RVCS for Damper Conditions during ULOHS Event.

5. Discussions

The RVCS is an additional heat removal system in the PGSFR during severe accident to maintain the integrity of the internal structures including the redan, reactor vessel, and so on. In order to evaluate the performance of the RVCS, the individual RVCS model is developed. When the damper is opened and closed, the required heat loss are tentatively assumed to 0.46 MW and 0.7 MW, respectively. When the RV temperature rises over 200 °C, the heat loss through the RVCS becomes 1.8 MW.

In order to evaluate the effect of the RVCS model in the unprotected event, the ULOHS event is analyzed for the PGSFR plant with and without the RVCS model. When the RVCS model with a closed damper is applied, the peak clad temperature is increased due to larger positive CRDL/RV reactivity feedback. However, when the RVCS model with an opened damper is applied, the peak clad temperature is reduced due to smaller positive CRDL/RV reactivity feedback.

Current RVCS model in MARS-LMR is simplified, so detailed modifications are necessary as follows:

- Realistic boundary condition in the concrete outer wall.
- View factors for entire structure surfaces
- Radiation model in the redan structure

The design parameters are tentatively assumed, because the RVCS design is not determined yet. Following design concern will be finalized in the near future. Then, the safety analysis will be re-analyzed with designed parameters.

- Designed RVCS dimensions, such as gap size, structure thickness, materials, and so on.
- Heat loss in the RVCS during normal operation
- If a damper is applied to the RVCS, damper operation logic and related heat losses.

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