Evaluation of Double Leakage at Primary Heat Transport Systems of Monju with Passive Safety Features

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Abstract. A sodium-cooled fast reactor shall maintain the reactor coolant level required for decay heat removal even in a sodium leakage accident. Monju, a prototype fast breeder reactor, has three primary heat transport systems (PHTSs) and has design measures to deal with coolant leakage from one location at the PHTS as a design basis accident (DBA). More severe events leading to a possible Loss of Reactor Level (LORL) such as double leakage at PHTSs, however, should be evaluated as design extension conditions (DECs).

JAEA has conducted a safety evaluation of impacts of double leakage at the PHTSs considering the passive safety features of Monju as a best-estimate evaluation for a DEC. The results show that the total amount of leaked sodium can be reduced by the depressurization of the cover gas resulting from the decrease in coolant inventory, i.e. negative pressure effects. The reactor coolant level required for decay heat removal, therefore, can be maintained with high reliability even under double leakage at the PHTSs.

Key Words: Monju, negative pressure effects, double leakage, Loss of Reactor Level (LORL)

1. Introduction

Monju is a loop-type prototype sodium-cooled fast reactor (SFR) with 714 MW thermal output, equipped with three primary heat transport systems (PHTSs). A PHTS consists of a reactor vessel (RV), an intermediate heat exchanger (IHX) and a primary circulation pump as shown in FIG.1. The upper parts of the RV and of the primary pump are filled with argon gas (cover gas), and the cover gas plenums are connected to each other with argon gas piping.

No pressure increase is required for the primary cooling system thanks to the high boiling point of sodium. In order to maintain the reactor coolant level even in a coolant leakage accident from one location at a PHTS, piping connecting the components are installed at high elevations and guard vessels (GVs) are installed under the RV, the IHX and the primary pump to retain leaked sodium.

However, more severe events leading to a possible Loss of Reactor Level (LORL) should be evaluated as design extension conditions (DECs). Then, JAEA has conducted an evaluation of double leakage at the PHTSs in consideration of the passive safety features as a best-estimate method, where this event leads to LORL by a conservative method used in DBA evaluation.

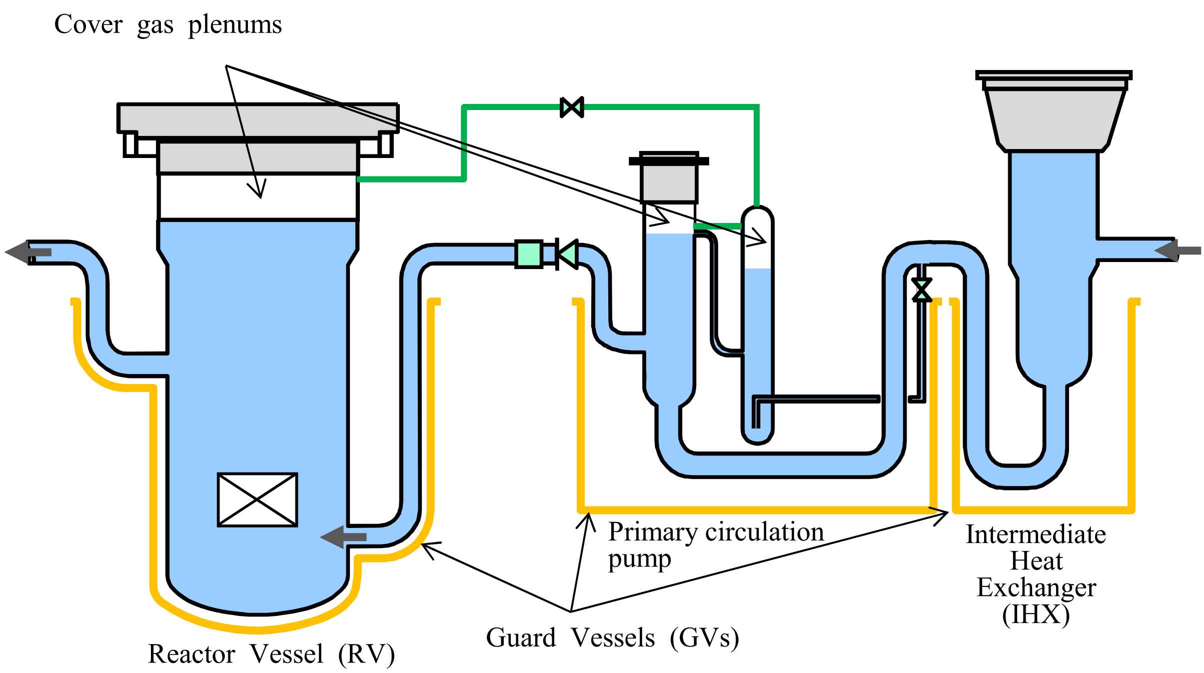

FIG. 1. Primary heat transport system of Monju.

2. Passive Safety Features (Negative Pressure Effects)

A conservative evaluation of DBA assumed no pressure decrease of the cover gas below the atmospheric pressure. However, once sodium leaks, the containment isolation valves are automatically closed and the argon gas supply to the PHTSs is stopped by the interlock system. The rotating plug over the RV is sealed by the freeze metal which is frozen during the normal plant operation. The airtightness of the cover gas boundary can be kept in the case of sodium leakage accidents and atmospheric air cannot leak into the cover gas plenums. Therefore the cover gas pressure will be getting lower as sodium leaks and reach under the atmospheric pressure, 101,330 Pa. In fact, the results show that the volume of cover gas plenum increases to more than double, and the cover gas pressure decreases to less than 70,000 Pa, where the initial cover gas pressure is 155,330 Pa. These effects (hereinafter “negative pressure effects”) could keep the reactor coolant level higher than the leaked sodium level in the GV as shown in FIG.2 and the total amount of leaked sodium can be reduced.

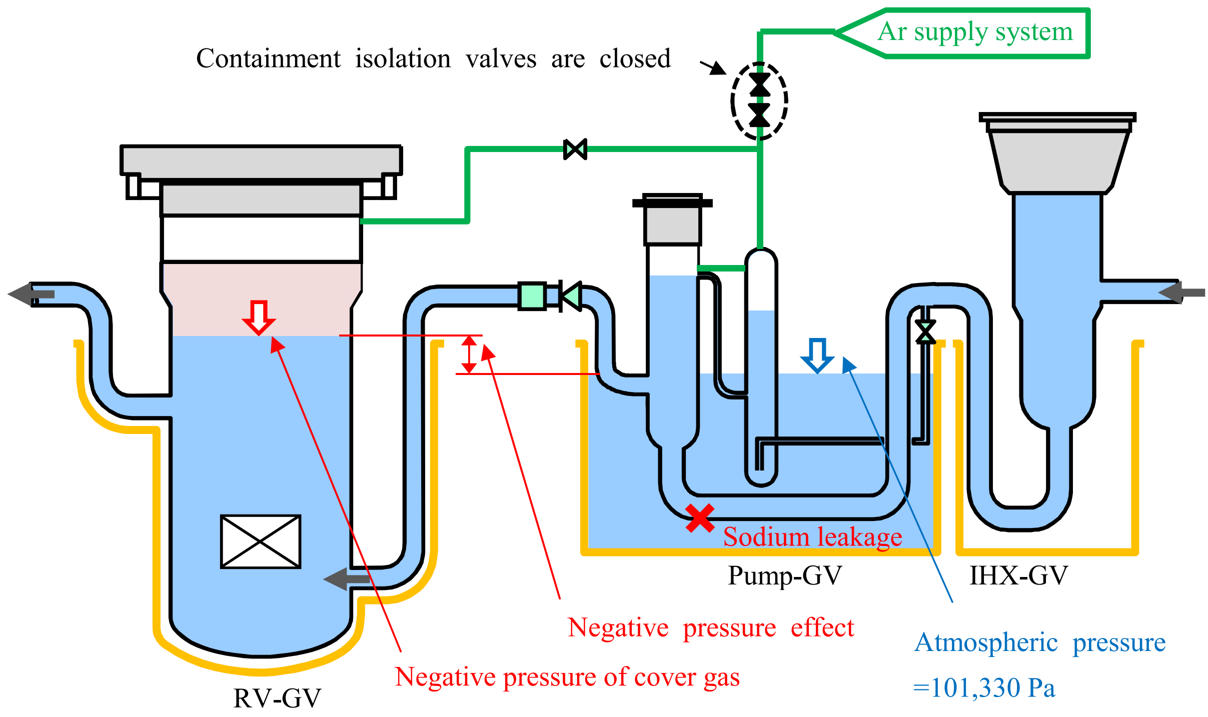

FIG. 2. Negative pressure effect.

3. Evaluation Conditions

Primary conditions considered in the evaluations are below.

- When the first leakage is detected, the reactor is shut down. At the same time, all the motors of the main pumps are stopped and the low speed motors (pony motors) begin to rotate. In addition, the pony motor of the leaked loop is stopped by hand from the main control room.
- The total amount of the sodium is assumed to shrink $54m^3$ in 15 hours accompanied by the decrease of the sodium temperature.
- A primary coolant leakage occurs in "PHTS piping", and the opening area of failure is 1/4Dt (D is a diameter of a pipe, t is a thickness of a pipe) from the study of crack growth under low pressure circumstances. [1].
- The second leakage occurs independently of the first leakage, and it is assumed to occur 24 hours after the first leakage according to the result of PRA of Monju, that is, the probability of the second leakage within 24 hours from the first leakage is negligibly small.
- All the sodium is pumped up from the charging tank (see FIG.3) to the RV after the first sodium leakage.
- Leaked sodium in the GV corresponding to the first leakage flows back into the PHTSs after the second leakage, because the internal sodium pressure of the first leakage point decreases below the external sodium pressure due to the second leakage. However, no leaked sodium is assumed to flow back into the PHTSs in consideration of the possibility of its freeze.

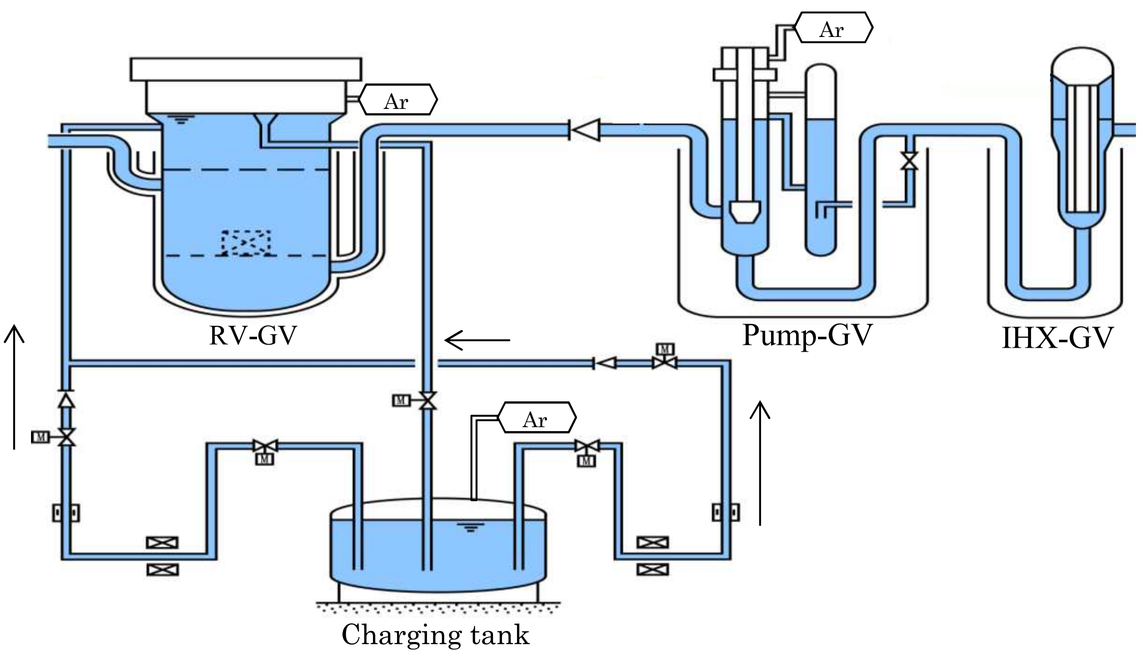

FIG. 3. Sodium charging system.

4. Success Criterion

The success criterion is to maintain the reactor coolant level high enough to keep the core cooling by the PHTSs. It is assumed that the reactor coolant level is 30 cm higher, including a margin, than the upper end of the RV outlet pipe. (see FIG.4)

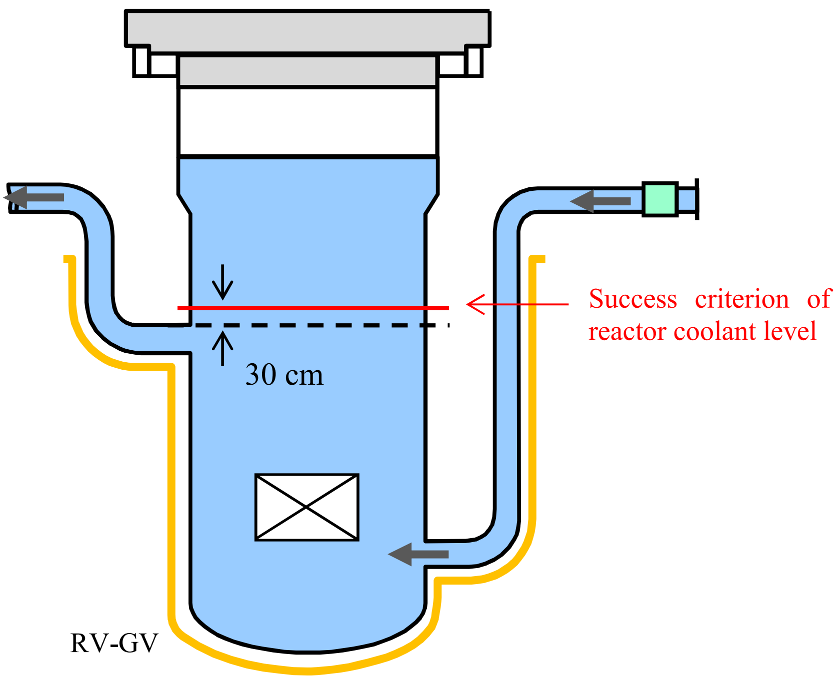

FIG. 4. Success criterion of reactor coolant level.

5. Evaluation Models

The main procedure of the evaluation consists of 3 parts;

STEP1 : calculations of the sodium leakage flow rate,

STEP2 : calculations of the sodium levels in the RV and the GVs, and

STEP3 : calculations of the cover gas pressure.

This procedure is repeated every time step. Each calculation model is described below.

STEP1 : calculations of the sodium leakage flow rate

The sodium leak flow rate is calculated based on the pipe internal/external pressure difference and flow resistance coefficient at the leakage point, and the area of the opening.

The sodium leakage flow rate Q_{leak} (m^3/h) is given by

$$Q_{leak} = A_{leak}\ V_{leak}$$

where A_{leak} (m^2) is the pipe leakage area. V_{leak} (m/s) is the leakage flow velocity, which is obtained by

$$V_{leak} = \sqrt{\frac{2g\Delta H}{C}}$$

where ΔH (m) is the pipe internal/external pressure difference, g (m/s^2) is gravitational acceleration and C (C is 1.0 or more) is flow resistance coefficient at the leakage point. In this paper, all the evaluations are conducted under the condition where C equals 1.0 to give the highest value to V_{leak} .

The internal pressure of the pipe is obtained by a summation of the cover gas pressure P_{CG} (Pa) and the head pressure of sodium. In the case of the leakage at an RV inlet pipe, the pump pressure H_{pump} (m), which is prepared as a design value corresponding to the number of operating pump pony motors, is also to be considered.

$$H_{pump} = \begin{cases} H_{pump}(\#\text{Operating pump pony motors}) & (Leakage\ point = RV\ inlet\ pipe) \\ 0 & (Leakage\ point = other\ point) \end{cases}$$

The external pressure of the pipe is the atmospheric pressure P_{atm} (Pa), when the sodium level in the GV H_{GV} (m), is lower than the height of leakage point H_{leak} (m). Then, using sodium density ρ_{Na} (k/m^3) and the sodium level in the RV H_{RV} (m), ΔH is given by

$$\Delta H = \frac{P_{CG} - P_{atm}}{\rho_{Na} g} + H_{RV} - H_{leak} + H_{\text{pump}}$$

On the other hand, when the sodium level in the GV H_{GV} is higher than the leakage point H_{leak}, the external pressure of the pipe is a summation of the atmospheric pressure $P_{atm,}$ and the head pressure of sodium above the GV. Thus, ΔH is given by

$$\Delta H = \frac{P_{CG} - P_{atm}}{\rho_{Na} g} + H_{RV} - H_{GV} + H_{\text{pump}}$$

STEP2 : calculations of the sodium levels in the RV and the GVs

The sodium inventory in the RV and the GVs is calculated each time based on the sodium mass balance and the sodium leakage flow rate. The sodium levels in the RV and the GVs are calculated based on the design data about the relations between the levels and the inventories.

STEP3 : calculations of the cover gas pressure

The cover gas pressure is calculated as an ideal gas based on the increase of the cover gas volume caused by the decrease of the reactor coolant level.

6. Evaluation Results

Selected locations of assumed leakage are shown in FIG.5, focusing low parts of a PHTS which give large differential load of sodium. No leakage at piping inside IHX-GV is selected, because IHX-GV has the smallest capacity among the GVs.

Table I lists the selected combinations of the leakage, in consideration of symmetricity of A to C loop.

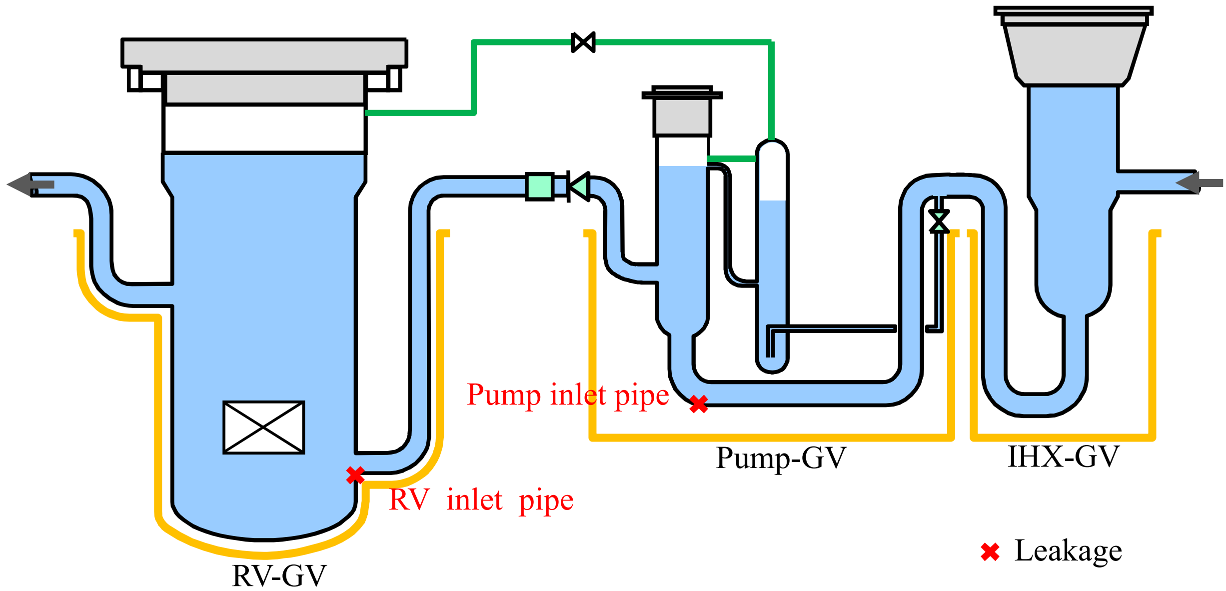

FIG. 5. Selected leakage locations.

TABLE I: SELECTED COMBINATIONS OF LEAKAGE.

No.	First leakage	Second leakage
1	Pump inlet pipe in loop A	RV inlet pipe in loop B
2	RV inlet pipe in loop A	Pump inlet pipe in loop B
3	Pump inlet pipe in loop A	Pump inlet pipe in loop B

The evaluation results are shown in Table II. The results show that all the combinations satisfy the criterion; the reactor coolant level is maintained 30 cm higher than the upper level of the RV outlet pipe.

As an example, FIG.6 shows the event progress of the combination No.1. When the first leakage (at the pump inlet pipe) is detected, the reactor is shut down and sodium in the charging tank is pumped up at the flow rate about 33 m^3 / hour to the RV. After all the sodium in the charging tank is pumped up (about 3 hours after the first leakage), sodium finishes to leak and the reactor coolant level continues to decrease due to the sodium shrink accompanied by the decrease of sodium temperature. When the sodium shrink ends (about 15 hours after the first leakage), the reactor coolant level finishes to decrease and the balanced condition of the first leakage is achieved.

After the second leakage (at the RV inlet pipe) occurs, the reactor coolant level decreases and the balanced condition of the second leakage is achieved about 1 hour after the second leakage.

FIG.7 shows the balanced conditions of the first and the second leakage of the combination No.1. Thanks to the negative pressure effect of the cover gas plenum, the reactor coolant level is maintained higher than the GV coolant levels. For example, at the first leakage, the reactor coolant level can be maintained about 2.6 m higher, and at the second leakage, it can be maintained about 4.4 m higher than the GV coolant levels corresponding to the leakage. As a result, the reactor coolant level required for decay heat removal is maintained, where this event leads to Loss of Reactor Level (LORL) without negative pressure effects.

TABLE II: RESULTS OF EVALUATIONS.

No.	First leakage			Second leakage			Satisfi-ability of the criterion	Note
	Leakage location	Balanced reactor coolant level*	Balanced cover gas pressure	Leakage location	Balanced reactor coolant level*	Balanced cover gas pressure		
		cm	Pa		cm	Pa		
1	Pump inlet	292	78,800	RV inlet	82	62,200	○	FIG.6 shows the event progress and FIG.7 shows the balanced conditions.
2	RV inlet	256	75,400	Pump inlet	146	66,500	○	
3	Pump inlet	292	78,800	Pump inlet	164	67,700	○	

CRITERION: the reactor coolant level is 30 cm higher than the upper end of the RV outlet pipe
*: above level of the upper end of the RV outlet pipe
○: satisfaction of the criterion

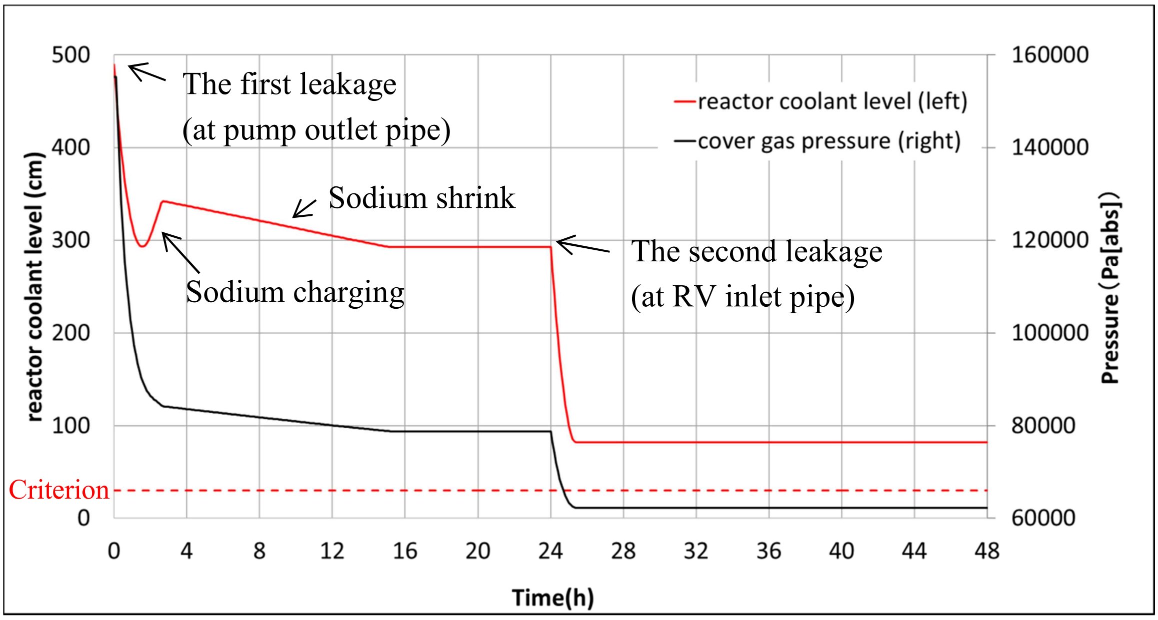

FIG. 6. Event progress of combination No.1.

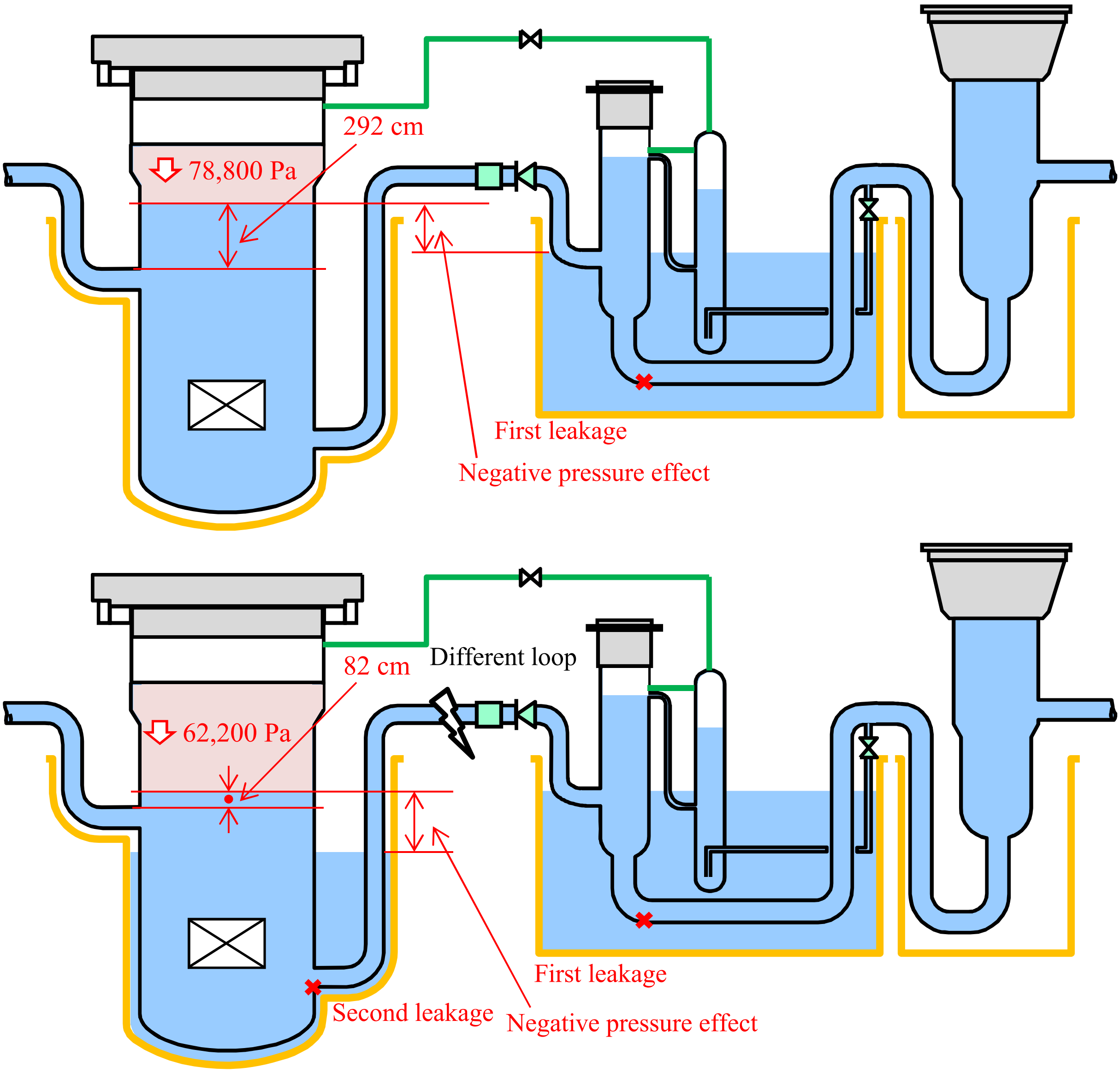

FIG. 7. Balanced conditions of the first and second leakage of combination No.1.

From the above, core-cooling by the PHTSs can be kept even in the double primary leakage accidents. However, it is of great benefit to prepare multiple and independent measures for the accidents of DECs. In fact, Monju has another cooling system used in maintenance of PHTSs (herein after "maintenance cooling system". See FIG.8). It has a cooling circuit below the RV outlet nozzle and the core-cooling can be kept even in the failure of the core-cooling by the PHTSs. Thus, LORL can be prevented with sound reliability by multiple preventive measures against it, independent of each other, in Monju.

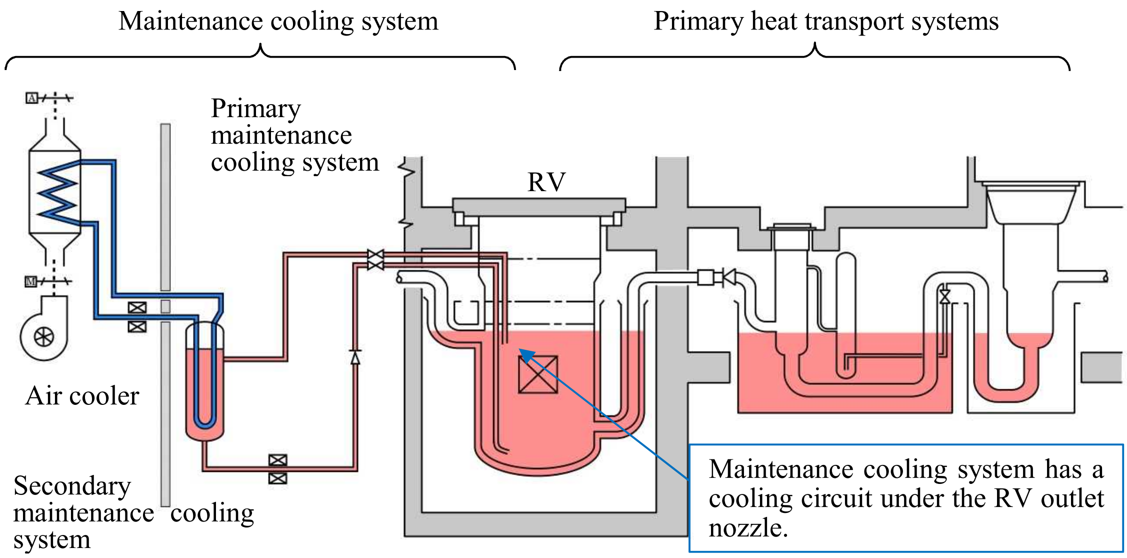

FIG.8. Maintenance cooling system.

7. Conclusion

This study has revealed that Monju can retain the reactor coolant level required for decay heat removal with high reliability even if a double leakage event occurs at the primary systems, thanks to the passive safety features (negative pressure effects).

ACKNOWLEDGEMENTS

The authors wish to express gratitude to T. Amada (FBR Engineering Co., Ltd.), F. Yamada (JAEA) and M. Arikawa (NESI Inc.), who gave us beneficial ideas and suggestions about evaluations and phenomena of double leakage at the primary systems.

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