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Investigation of Non-cooldown SG Secondary Condition on the Natural Circulation Cooling Procedure

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Abstract: In typical pressurized water reactor (PWR), in case that one steam generator (SG) cannot be credited for the primary cooldown, it is necessary to homogenize primary coolant temperature among loops using at least one reactor coolant pump (RCP) for the plant cooldown. If the natural circulation condition is established due to unavailability of all the RCPs, the continuous cooldown using intact SGs causes to disturb the smooth depressurization because it leads to void generation in the top of the non-cooldown SG tube where the high temperature coolant is remained. For this purpose, W.Sakuma, et al.[1] suggested the outline of asymmetric cooldown procedure without any RCPs restart. Since the suggested procedure is based on only one secondary condition (SG dry-out) of non-cooldown SG, and hence the impact of difference of the secondary condition should be investigated. In this paper, the sensitivity analyses were performed to confirm the impact on the asymmetric cooldown procedure, and consequently, it was confirmed that the coolable range used in the procedure was expanded if the water inventory exists in non-cooldown SG. Therefore it was concluded that the coolable range which was defined with the SG dry-out condition in non-cooldown SG can be conservatively applied for the operating procedure.

Keywords: *PWR, natural circulation, loop unbalanced condition, cooling procedure, M-RELAP5 code.*

I. INTRODUCTION

In typical pressurized water reactor (PWR), the primary system cooldown is performed by using main steam relief valves (MSRVs) in secondary system. The primary system is cooled down and depressurized by MSRVs until the connection of residual heat removal system (RHRS) is achieved. In case that one steam generator (SG) is not available for cooldown due to the valve failure or SG dry-out after steam line break (SLB) or feedwater line break (FLB), the primary temperature difference among loops occurs in consequence of asymmetric cooldown using MSRVs in only intact SGs. The continuous asymmetric cooldown could cause void generation by decompression boiling at the U-tubes of non-cooldown SG because high temperature coolant tends to be remained in non-cooldown loop. In order to avoid the occurrence of temperature difference among loops under asymmetric cooldown condition, restart of at least one reactor coolant pump (RCP) is required in emergency operating procedure for typical PWR in Japan at the moment.

In addition, there is a possibility that all RCPs are failed if the earthquake or the fire occurs. Hence, the establishment of asymmetric cooldown procedure, which does

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not require the restart of RCPs under natural circulation condition in primary system, can contribute to the safety enhancement for typical PWR.

As an experimental investigation, asymmetric cooldown tests under natural circulation condition have been already reported using PKL[2] and Large Scale Test Facility (LSTF)[3][4]. Based on the numerical calculation, W. Sakuma, et al.[1] suggested the outline of the asymmetric cooldown procedure under the natural circulation condition with the coolable range between amount of decay heat and temperature difference of non-cooldown loop. Since the coolable range is defined based on the numerical calculation assuming the same condition as LSTF and dry-out in affected SG, it is necessary to consider the secondary condition (dry-out or not) of the non-cooldown SG. The purpose of this paper is to show the impact of secondary condition on the coolable range. In this paper, Mitsubishi Heavy Industries, Ltd. (MHI) performed the sensitivity analyses assuming that the water inventory exists in the non-cooldown SG secondary side, and confirmed the impact on the coolable range.

II. NUMERICAL CALCULATION FOR ASYMMETRIC COOLDOWN TEST UNDER NATURAL CIRCULATION CONDITION

A. Outline of asymmetric cooldown test

Asymmetric cooldown tests have been already performed in PKL and LSTF to investigate behavior of loop unbalanced natural circulation[2][3]. These asymmetric cooldown tests have reported that continuous cooldown is feasible by stepwise MSRV operation, which repeats opening and closing valve, under loop unbalanced condition.

OECD/NEA ROSA-2 Project conducted asymmetric cooldown test in LSTF in 2011[3]. In LSTF, it was also confirmed that flow stagnation did not occur in any loops by the stepwise cooldown procedure under loop unbalanced natural circulation condition. The test result reported that inverse heat transfer from SG to the primary side occurs in non-cooldown SG and it generates the counter driving force which disturbs the natural circulation flow.

B. Mechanism of natural circulation flow stagnation

The test conducted in LSTF has reported that counter driving force generated in non-cooldown SG disturbs natural circulation in primary system[3]. In natural circulation condition, driving force is generated by coolant density difference between inlet and outlet in reactor vessel (RV) and SG. A schematic and the driving for of natural circulation are shown in Figure 1 and Eq.1 as already reported[1].

$$\boldsymbol{\Delta P_{Loop} = \Delta P_{RV} + \Delta P_{SG}}$$
$$\boldsymbol{= \int_{in(RV)}^{out(RV)} \rho_{RV} g dz + \int_{in(SG)}^{out(SG)} \rho_{SG} g dz} \quad \text{Eq. 1}$$

In Eq.1, P, ρ and g mean natural circulation driving force, coolant density and acceleration of gravity, respectively. The Loop, RV and SG described as the subscript mean the primary loop, reactor vessel and steam generator. The driving force is the same as water head difference between lower side and upper side.

In non-cooldown loop, SG outlet temperature becomes higher than inlet temperature due to inverse heat transfer from the SG to the primary side, and this temperature difference causes the counter driving force. This generates negative driving force (ΔP_{SG}) which disturbs the natural circulation in non-cooldown SG. In order to maintain the natural circulation flow condition, the total driving force (ΔP_{RV} + ΔP_{SG}) in the primary loop must be positive. This means that absolute value of driving force (ΔP_{SG}) of the natural circulation by non-cooldown SG must be smaller than the driving force (ΔP_{RV}) in RV (i.e. Eq.2).

$$\Delta P_{RV} > |\Delta P_{SG}| \qquad \text{Eq.2}$$

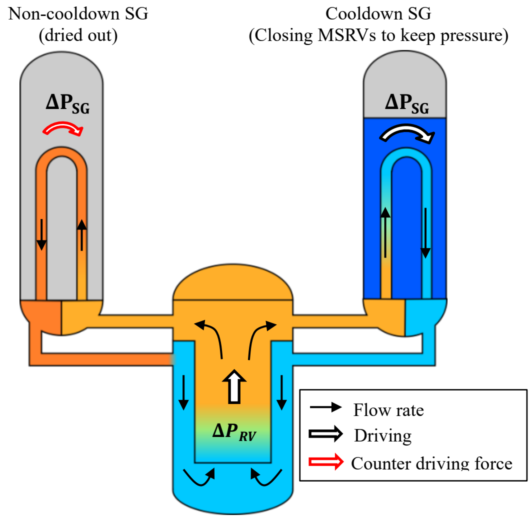


Fig.1. Schematic of natural circulation behavior with non-cooldown SG (LSTF test condition)

III. ASYMMETRIC COOLDOWN PROCEDURE WITHOUT FLOW STAGNATION USING AVAILABLE MEASUREMENTS

A. Parameters to be measured for asymmetric cooldown procedure

The mechanism of flow stagnation occurrence in non-cooldown loop described in section II has been confirmed by the simulation result[1] using M-RELAP5[5], which is RELAP5-3D based code improved by MHI. The results mean that the flow stagnation during natural circulation condition occurs when the counter driving force generated in non-cooldown loop exceeds driving force in RV. It is important for operators to predict the flow stagnation using the plant parameters available from main control room (MCR).

One of the possible ways which is suggested by W.Sakuma, et al.[1] is to observe temperature difference in intact and affected loop. The driving force in RV and SG described in Eq.1 are given by Eq.3 and Eq.4 since the coolant density is proportional to coolant temperature. The driving force in RV is decided by the inflow ratio (n) of intact and the affected cold leg temperature. Location of each parameter is defined in Figure 2.

$$\Delta P_{RV} \propto \Delta T_{RV} = T_{RV}^{inlet} - T_{RV}^{outlet}$$
$$\cong \left\{ nT_{Cold}^{intact} + (1-n)T_{Cold}^{affect} \right\} - T_{Hot}^{intact}$$
Eq.3

$$\Delta P_{SG}^{affect} \propto \Delta T_{SG}^{affect} = T_{SG}^{inlet} - T_{SG}^{outlet}$$
$$\cong T_{Hot}^{affect} - T_{Cold}^{affect} = \Delta T_{Loop}^{affect}$$
Eq.4

The inflow ratio (n) is defined by the fraction of the intact loop flow rate to the total flow rate in Eq.5.

$$n = \frac{F_{intact}}{F_{total}} = \frac{F_{intact}}{F_{intact} + F_{affect}} \qquad \text{Eq.5}$$

Since the flow rate in intact loop is dominant in RV coolant flow, the driving force in RV is simply given by Eq.6 (i.e. $n \cong 1$).

$$\Delta P_{RV} \propto T_{Hot}^{intact} - T_{Cold}^{intact} = \Delta T_{SG}^{intact} \qquad \text{Eq.6}$$

In addition, temperature difference between inlet and outlet in intact SG is almost proportional to decay heat at steady state condition (Eq.7).

$$\Delta T_{SG}^{intact} \propto Q_{decay} \qquad \text{Eq.7}$$

From these conversion equations, the operators can use the temperature difference of affected SG (ΔT_{Loop}^{affect}) and decay heat in order to predict the flow stagnation occurrence. It is noted that the amount of decay heat can be estimated according to core design and operational history.

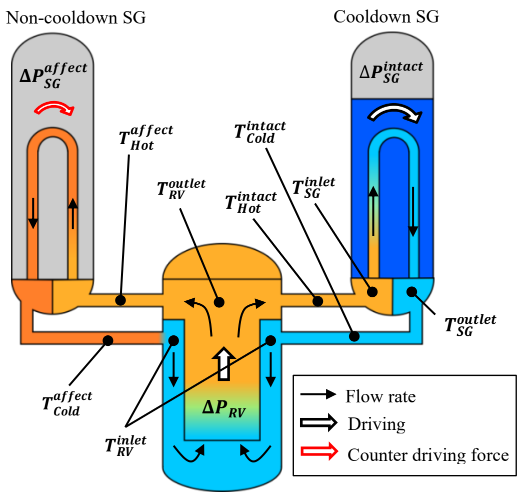


Fig.2. Location of each parameter

B. Asymmetric cooldown range without flow stagnation

The coolable range in which the flow stagnation does not occur at loop unbalanced condition without RCPs is represented in Figure 3. In addition, Figure 4 is given because the decay heat is inverse proportional to time after reactor trip. Figure 4 makes it easy to judge occurrence of flow stagnation. The operators have to keep temperature difference between inlet and outlet in non-cooldown SG smaller than dashed line in Figure 4 to avoid flow stagnation.

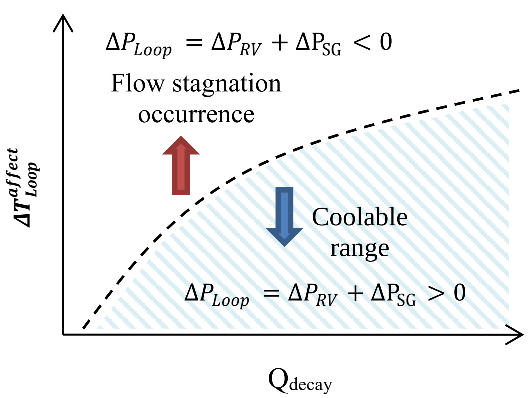


Fig.3. Coolable range at loop unbalance without RCPs using decay heat

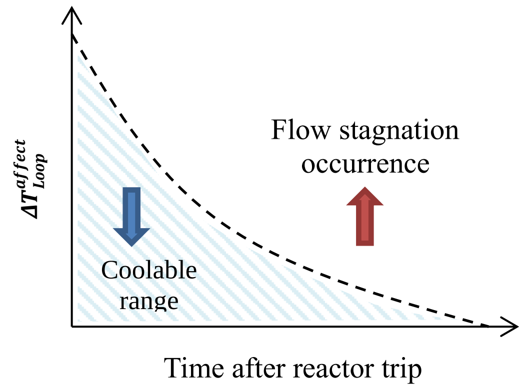


Fig.4. Coolable range at loop unbalance without RCPs using time after reactor trip

It is noted that the coolable range has been defined by the sensitivity analyses[1] assuming the various condition of cooldown rate and residual heat based on LSTF test. Though LSTF test assumes the dry-out condition in non-cooldown SG, there is a possibility to exist the water inventory in non-cooldown SG in actual PWR plants when the operator performs the asymmetric cooldown without RCPs operation. Therefore, it is necessary to consider the impact of the difference of the non-cooldown SG water inventory condition (SG dry-out or not).

IV. INVESTIGATION OF IMPACT OF SECONDARY SIDE CONDITION IN NON-COOLDOWN SG

A. Numerical analysis condition

If the water inventory exists in the secondary side of non-cooldown SG, the heat transfer between primary and secondary side is different comparing with the SG dry-out case. The different two initial conditions are assumed to investigate the impact of the secondary side condition (dry-out or not) of non-cooldown SG. Table I shows the analysis condition of initial plant state.

Table I. Analysis condition of initial plant state

	Case 1[1]*	Case 2
Primary side		
Core power	1.29MW	Same as Case1
Initial pressure	11MPa	Same as Case1
RCPs	All RCPs stopped	Same as Case1
Secondary side (SG-1: Non-cooldown SG)		
Water inventory	Dry-out	Not dry-out
MSRV	Available	Unavailable
Secondary side (SG-2: Cooldown SG)		
Water inventory	Not dry-out	Same as Case1
MSRV	Available for cooldown	Same as Case1

*The condition of Case 1 is the same as LSTF test.

In addition, the sensitivity analyses of various cooldown rate and decay heat were performed to define the cooldown possible range for operating procedure. The cooldown rate of 20°C/hr, 30°C/hr, 60°C/hr and 120°C/hr, and the decay heat of 0.45%, 0.9%, 1.8% and 3.6% were assumed.

B. Numerical analysis result

As mentioned in section III, the counter driving force generated in non-cooldown loop is estimated by the temperature difference between hot and cold temperature (ΔT_{Loop}^{affect}). The temperature difference in the sensitivity analyses are summarized in Table II.

Table II. ΔT_{Loop}^{affect}(°C) at flow stagnation occurrence (left part: Case 1[1], right part: Case 2)

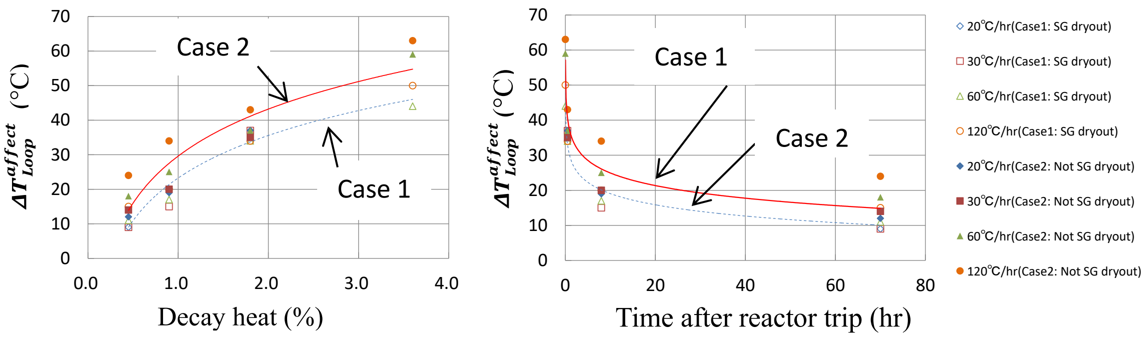
Cooling rate (°C/h)	Decay heat (%)**			
	0.45	0.9	1.8	3.6
20	9/12	20/19	-*/37	-*/-*
30	9/14	15/20	37/35	-*/-*
60	11/18	17/25	34/37	44/59
120	15/24	20/34	34/43	50/63

*Flow stagnation didn't occur.
**Percentage of core power of actual PWR plant

The threshold of cooldown possible range described by the temperature difference ΔT_{Loop}^{affect} and decay heat are shown for Case 1[1] and Case 2 in Figure 5(1). In addition, Figure 5(2) shows the cooldown possible range with the time after reactor trip which is converted from the decay heat using the EOC (end of cycle) core of typical PWR plant.

From these analyses results, the coolable range in the not SG dry-out case (Case 2) expands comparing with the SG dry-out case (Case 1) as shown in Figure 5. If the water inventory exists in the secondary side of non-cooldown SG, the heat transfer between the primary and secondary side increases. The heat transfer from secondary side to primary side in non-cooldown SG induces the counter driving force against the natural circulation flow in the primary circuit. Due to the difference of heat transfer, the temperature distribution in the primary side of U-tube of non-cooldown SG differs between Case 1 and Case 2. Figure 6 shows the schematic of temperature distribution in the primary side of U-tube. As shown in Figure 6, the primary temperature in U-tube in Case 2 reaches to the secondary side temperature at the lower level than Case 1. Because the smaller amount of low temperature coolant in riser region of U-tubes causes less counter driving force from the static head viewpoint, Case 2 leads smaller counter driving force, and expands the coolable range.

As an example, the relationship between temperature difference ΔT_{Loop}^{affect} in the primary loop connected with non-cooldown SG and the driving force generated non-cooldown SG is described in Figure 7 for the case of 0.9% decay heat and 60°C/h cooling rate. The driving force generated by non-cooldown SG was derived from the following equation.

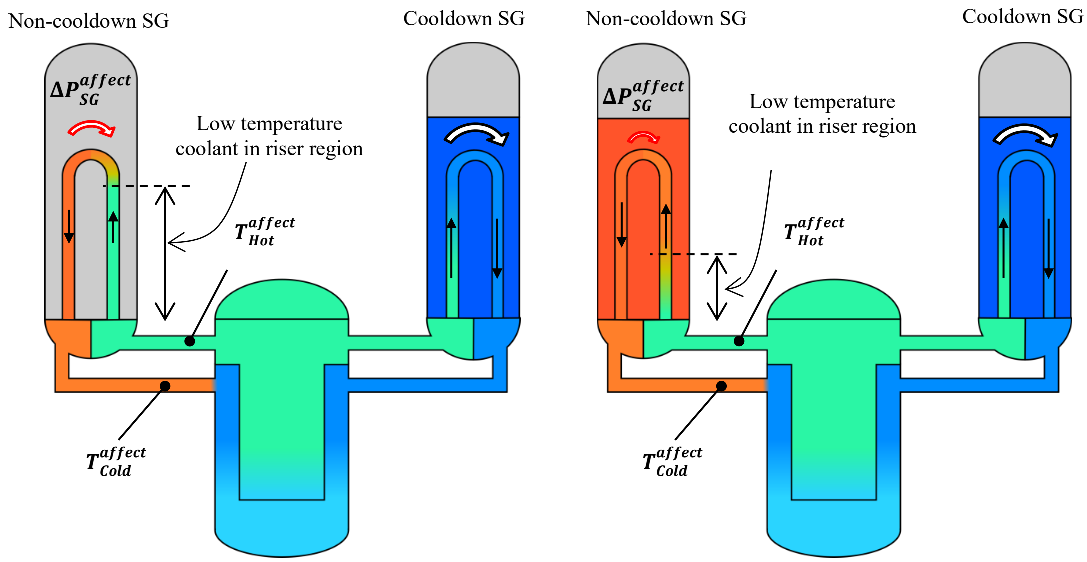


(1) Coolable range depending on decay heat (2) Coolable range depending on time after reactor trip

Fig.5. Coolable range

$$\Delta P_{SG}^{affect} = \int_{in(SG)}^{out(SG)} \rho_{SG} g dz \qquad \text{Eq. 8}$$

In Case 1, the flow stagnation occurred when the temperature difference of affected loop was about 17°C as shown in Table 2. When the temperature difference reached about 17°C, the counter driving force of Case 1 was larger than Case 2. From this result, it was confirmed that the counter driving force with SG dry-out condition is larger than not SG dry-out condition even if there is the same temperature difference.



Case 1: SG dry-out Case 2: Not SG dry-out

Fig.6. Schematic of temperature difference of U-tube

C. Consideration of implementation into operating procedure

It was confirmed that the cooldown possible range defined by the sensitivity studies performed with the assumption of the dry-out condition in non-cooldown SG was slightly narrower than the case of not SG dry-out condition. Therefore the cooldown possible range based on the SG dry-out condition can be conservatively applied in the operating procedure regardless of the secondary condition in non-cooldown SG.

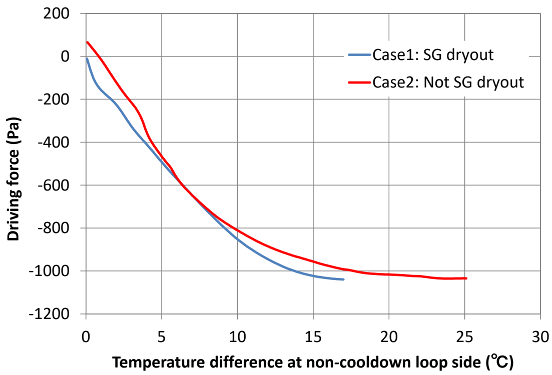


Fig.7. Relationship between temperature difference and driving force in the primary loop connected with non-cooldown SG

V. FUTURE WORK TO APPLY OPERATING PROCEDURE

In the previous study[1] and section IV, the simple method using decay heat and temperature difference between affected SG was suggested.

The result showed that driving force which determines natural circulation flow rate is important to estimate flow stagnation. The driving force generated in loop unbalanced condition depends on a height in RV and SGs. It was expected that almost of the result of the test and the simulation could be applied to PWR plants because LSTF has same height with typical PWR. However, scaling effect regarding to coolant mixing in RV should be considered. For LSTF, diameter of RV is smaller than typical PWR. This means that coolant which flows into RV tends to mix easier in RV than PWR plants. Therefore, it is needed to confirm mixing phenomena in RV for PWR plants under loop unbalanced natural circulation condition due to asymmetric cooldown.

Indeed, number of non-cooldown SGs should be also considered. In LSTF's test, 1 out of 2 SGs was assumed as affected SG. It is needed to evaluate whether number of affected loop affects natural circulation stagnation or not. There is a possibility that cooling possible range becomes very narrow if they affects natural circulation stagnation occurrence. In this situation, alternative operation is required to establish cooldown wish smooth depressurization under loop unbalanced natural circulation condition.

VI. CONCLUSIONS

The impact of the secondary condition in non-cooldown SG on the cooldown possible range was evaluated. In case that the water inventory exists in non-cooldown SG, the cooldown possible range is expanded due to the increased heat transfer and the counter driving force generated at non-cooldown SG becomes smaller. Therefore it is concluded that the cooldown possible range which is defined based on the assumption of SG dry-out condition in non-cooldown SG can be conservatively applied for the operating procedure. However, more detailed investigation is needed to apply the result to actual PWR plants.

NOMENCLATURE

ΔP	Driving force (i.e. differential pressure) (Pa)
ΔP_{Loop}	Total driving force in a loop(Pa)
ΔP_{SG}	Driving force generated in SG (Pa)
ΔP_{RV}	Driving force generated in RV (Pa)
ρ	coolant density (kg/m^3)
ρ_{SG}	ρ in SG (kg/m^3)
ρ_{RV}	ρ in RV (kg/m^3)
g	gravitational acceleration (m/sec^2)
ΔT_{RV}	Differential temperature between inlet and outlet in RV (°C)
T_{RV}^{inlet}	Inlet coolant temperature of RV

	(°C)
T_{RV}^{outlet}	Outlet coolant temperature of RV (°C)
T_{Hot}^{intact}	Hot leg coolant temperature at an intact side (°C)
T_{Hot}^{affect}	Hot leg coolant temperature at an affect side (°C)
T_{Cold}^{intact}	Cold leg coolant temperature at an intact side (°C)
T_{Cold}^{affect}	Cold leg coolant temperature at an affect side (°C)
ΔT_{SG}^{affect}	Differential temperature between inlet and outlet in affected SG (°C)
ΔT_{Loop}^{affect}	Differential temperature between hot leg and cold leg in affected SG (°C)
T_{SG}^{inlet}	Inlet temperature of affect SG (°C)
T_{SG}^{outlet}	Outlet temperature of affect SG (°C)
F_{total}	Total RV inlet flow rate (kg/sec)
F_{intact}	RV inlet flow rate from intact loop (kg/sec)
F_{affect}	RV inlet flow rate from affect loop (kg/sec)
Q_{decay}	Decay heat (W)

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