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The Gravity Makeup on the LORHR Event during Mid-loop Operation for APR1400

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1. Introduction

For the loss of cooling during the mid-loop operation, the plant needs to sustain sufficient time for operator action without any AC power. This concern is raised after the Fukushima accident. Especially, in addition to the loss of residual heat removal (LORHR), if the AC power is unavailable including the alternative diesel generator, the passive makeup using gravity feed will provide sufficient time before core uncovery.

This paper is to investigate means of the available gravity makeup after the event to prevent or sustain the core uncovery and fuel failure for the typical advanced power reactor nuclear power plants (APR1400).

Unlike the OPR1000 (optimized power reactor 1000 nuclear power plants), the refueling water storage tank of APR1400 cannot be used for gravity makeup since it is located on the bottom of the containment with a lower elevation than the reactor vessel. So, the other means of gravity makeup and their effect on the core uncovery are accounted.

The use of the water used for the cask loading pit (CLP) during refueling or the safety injection line filling tank (SIFT), which are not designed for gravity makeup during the event, and safety injection tanks (SITs) are considered as the alternative source of makeup feed.

The results show that gravity makeup of a SIT provides a sufficient operator action time for the LORHR with the station black out (SBO) during the mid-loop operation for the APR1400.

2. Analysis Method of LORHR

A realistic and best estimate analysis method is applied and reasonable operating conditions are assumed for the analysis of LORHR event since this event is categorized as a beyond design basis event (BDBE). RELAP5/MOD3.3-patch 4 [1] is used for the analysis of the thermal-hydraulic behavior in the reactor coolant system including the core. The analysis is performed for the event during the mid-loop operation with pressurizer (PZR) manway open for the typical APR1400.

The RELAP5 node diagram for the LORHR is provided in Figure 1.

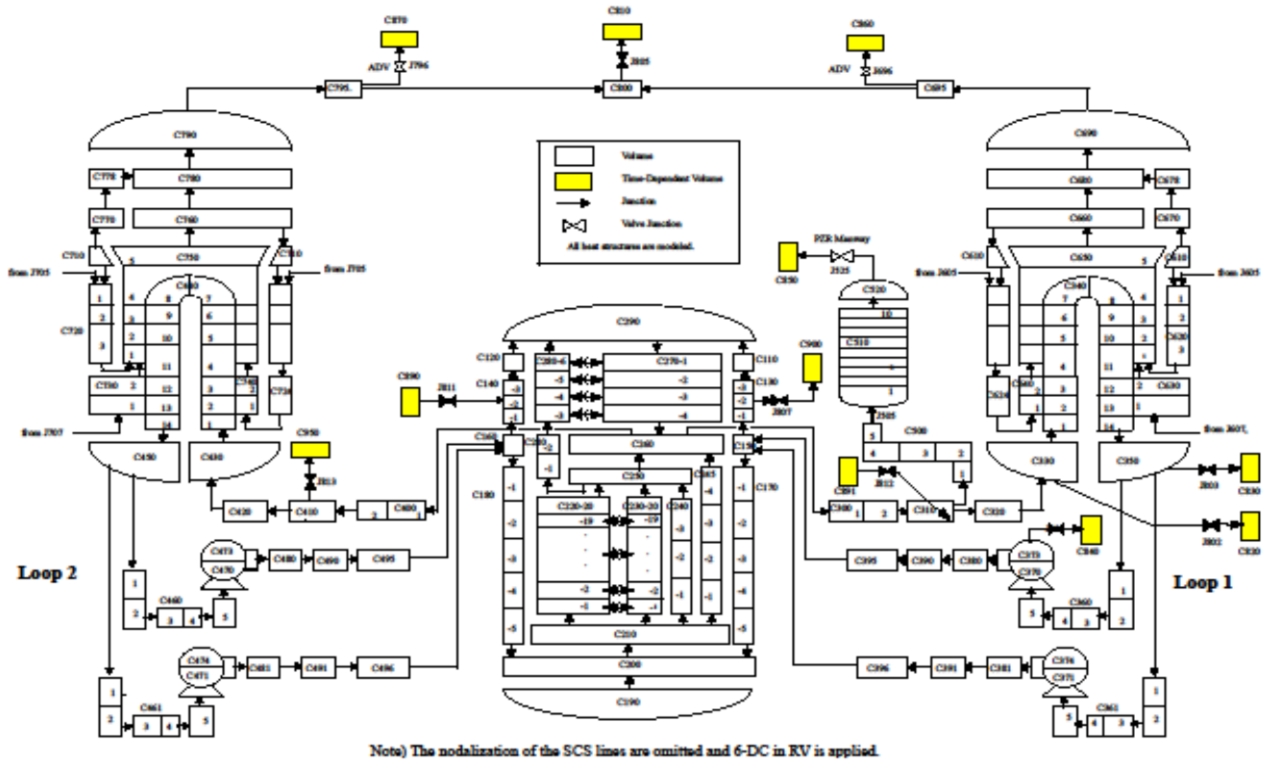

Figure 1 RELAP5 Node Diagram for LORHR

3. Major Assumptions and Initial Conditions

Major assumptions and initial conditions for the LORHR event analysis are based on the normal operation status of the plant outage.

A limiting situation of the LORHR event such as the mid-loop operation with PZR manway opening is considered since the RCS inventory is the minimum and RCS pressure is the lowest for steaming. Other major assumptions used in the LORHR analysis are as follows:

- 4 days after reactor shutdown which is typical outage duration for the mid-loop operation.
- The decay power is based on the burn up of 54,000 MWD/MTU (3 cycles of 18-month fuel) for the equilibrium core.
- ANS2005 standard decay heat curve [2] considering 2-sigma (8%) uncertainty with the nuclides of U^{235}, U^{238}, Pu^{239}, Pu^{241} for the equilibrium cycle of Plus7 fuel.
- The calculated decay heat power is 18 MWt.
- SGs are considered as inactive. So, no heat transfer through u-tubes is considered.
- Initial hot leg level is considered as the centerline of hot leg which is 2 inches lower than the low-low level alarm of mid-loop operation.
- Initial steady state is simulated using one train of the shutdown cooling system using the maximum constant flow of 250 kg/s.
- Assumed initial hot leg temperature is the maximum of 135 ^{o}F .
- No reactor coolant flow by reactor coolant pump (RCP).
- Depressurized SITs (1 atm) are available for manual control.

Reasonable and conservative initial conditions for the LORHR analysis are assumed as Table 1.

Table 1 Initial Condition for LORHR

Parameters	Values	Remark
PZR Pressure	101,325 Pa (1 atm)	-
Hot Leg Temperature	57.22 ^{o}C (135 ^{o}F)	Max
RCS Level	Center line of hot leg	2-in lower
RC Flow by RCP	NA	No RCP
Decay Heat	18 MWt	-
SGs for Cooldown	Inactive	dry
SCS HX Flow Rate	250 kg/s (3,970 gpm)	Max
SIT Pressure	101,325 Pa (1 atm)	-

4. Analysis Results

4.1 Cases Analyzed for Gravity Makeup

To investigate the means of makeup using gravity feed for the loss of all AC power, the LORHR event with PZR manway open during the mid-loop operation is analyzed as a base case.

Possible means of makeups are CLP, SIFT and SITs according to the APR1400 design. The operator action for the makeup is assumed to begin 1 hour after the event.

The hot leg pressure behaviors are provided in Figure 2 for base case, CLP makeup, SIFT makeup and SIT makeup considering the injection point through DVI and hot leg. As shown in this figure, the RCS pressure is increased up to 2 bars before 1 hour and increased. For SIT case, the pressure is decreased just after the injection but increased above 2.3 bars due to the longer steam formation. The makeup from CLP and SIFT cases show that there is no impact on the pressure behaviors due to the higher RCS pressure, the large flow resistance and low elevation head. The gravity flow from CLP, SIFT and SIT through DVI and hot leg are provided in Figure 3 & 4.

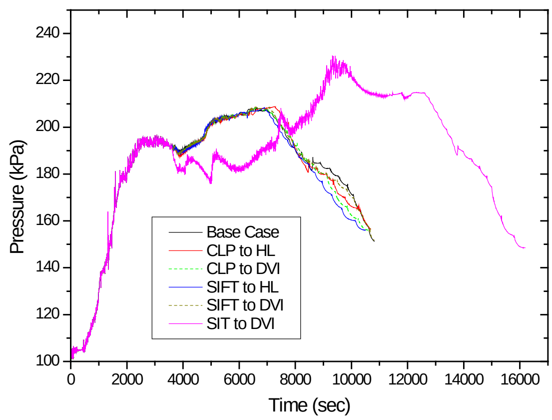

Figure 2 Comparison of Hot Leg Pressure Behaviors

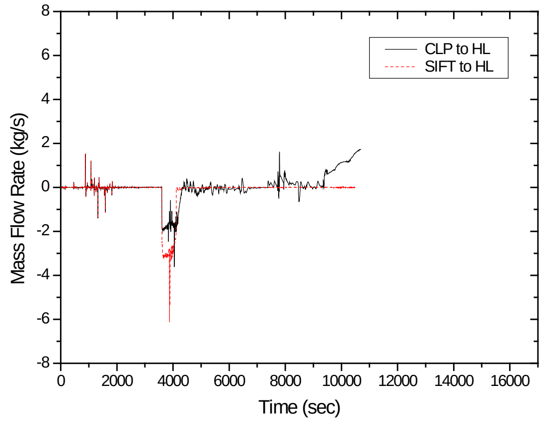

Figure 3 Makeup Flow Rate to Hot Leg

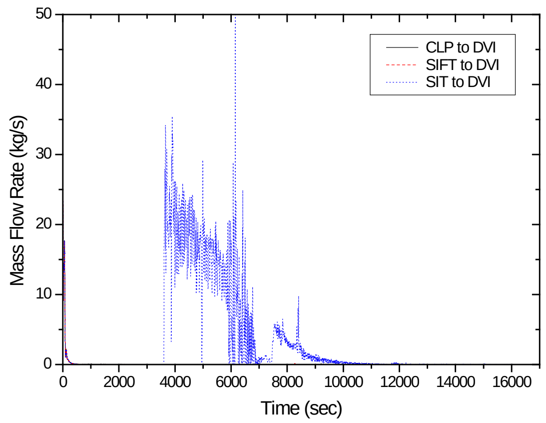

Figure 4 Makeup Flow Rate through DVI

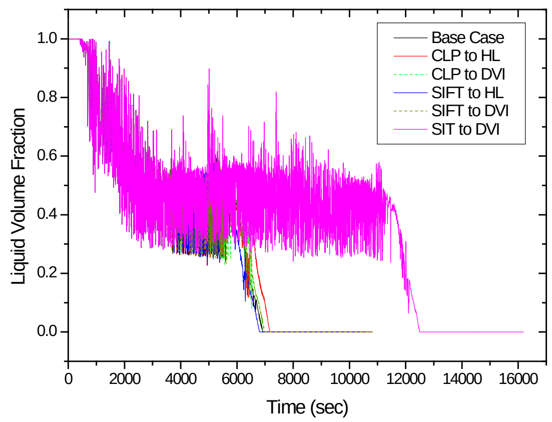

Figure 5 Liquid Volume Fraction of Upper Plenum

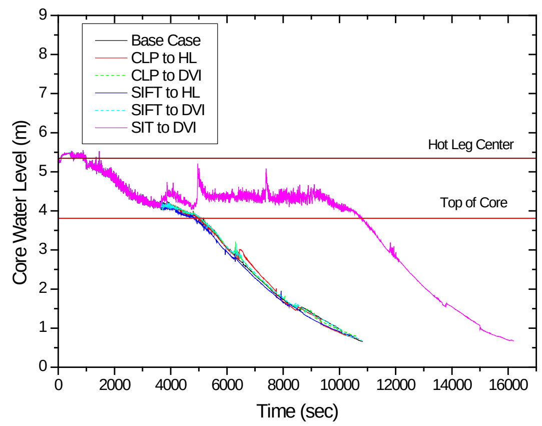

Figure 6 Core Collapsed Level Behaviors

The core uncovery time is determined as the time of no liquid in the lower upper plenum just above the core. As shown in Figure 5, the core uncovery time of SIT case is dominantly increased.

The corresponding core and downcomer collapsed level behaviors are compared in Figure 6 and 7, respectively. The SIT makeup maintains the core level reasonably but the CLP or SIFT makeup has no impact on the core level. Only SIT case provided a sufficient level increase in the downcomer as shown in Figure 6.

The fuel cladding temperatures are compared in Figure 8 providing delayed time of fuel failure for SIT makeup only.

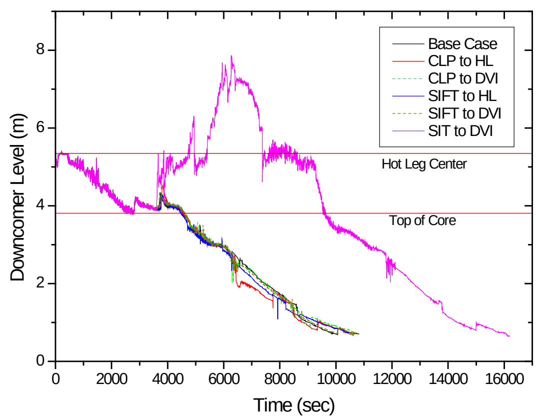

Figure 7 Downcomer Collapsed Level Behaviors

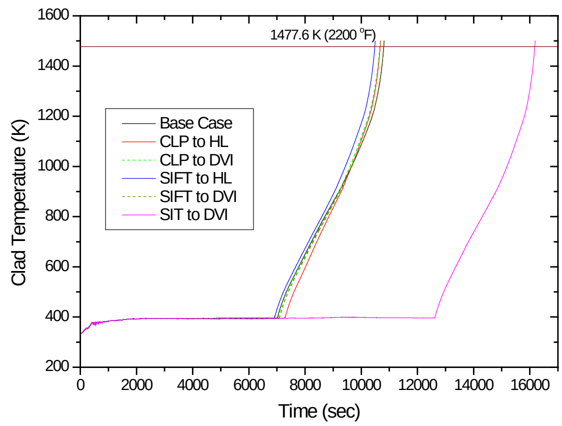

Figure 8 Fuel Cladding Temperature Behaviors

4.2 Studies on the SIT Makeup

For the SIT makeup, the makeup time with 30 minutes and 2 SITs makeup with another SIT (2-SIT case) are additionally considered. For 2-SIT case, the second SIT is provided 1 hour after first SITs feed or 5,400 sec (1.5 hr) after the event.

Figure 9 compares the pressure behaviors and provides a more fast increase for 30 min case than 1 hr case due to the fast feed and steam generation (Figure 10). Figure 11 shows the liquid decrease in SIT below the fluidic device (FD). As expected, the pressure of 2-SIT case is maintained high and the flow from the second SIT is delayed due to the high pressure (Figure 10 and 11).

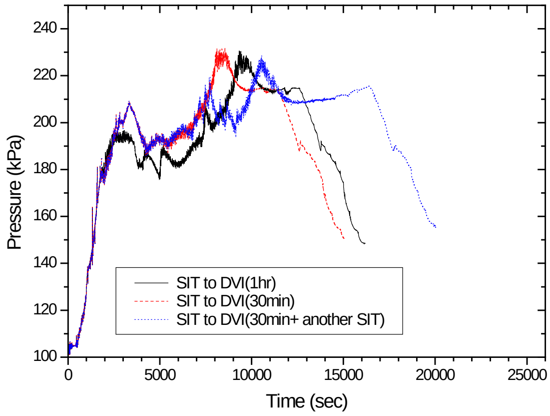

Figure 9 Comaprison of Hot Leg Pressures

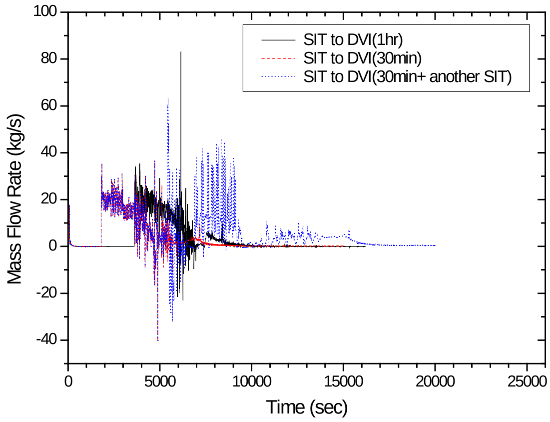

Figure 10 Feed Flow Rates from SIT

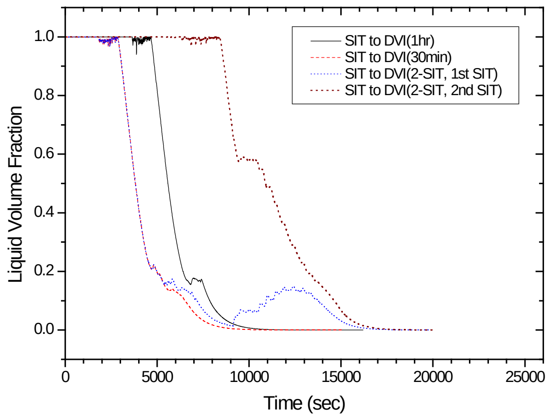

Figure 11 Liquid Variation of SIT below FD

The earlier feed flow provides a larger steam discharge through the PZR manway and thus fast decrease in core level up to 5,000 seconds as in Figure 12. 2-SIT case continuously delays the core level maintaining the core uncovered as in Figure 12. The corresponding peak clad temperatures (PCTs) are also delayed as compared in Figure 13.

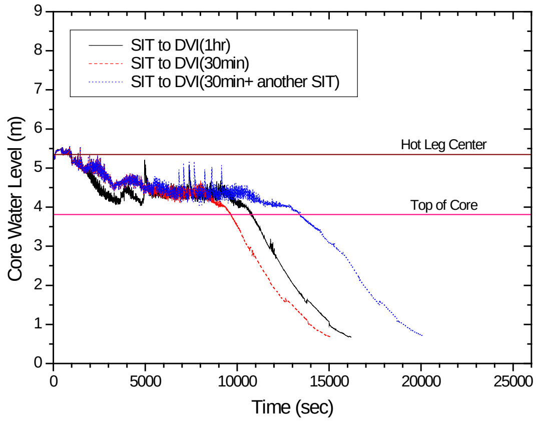

Figure 12 Comparison of Core Collapsed Levels

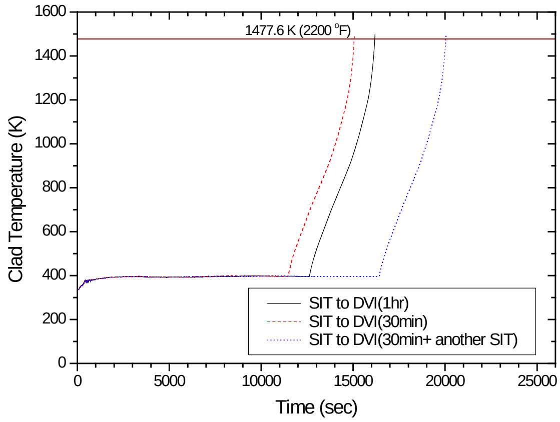

Figure 13 Comparisons of Fuel Cladding Temperatures

The case with 2 SITs provides a delayed PCT increase and extends the time of fuel failure about 5,000 sec from 1 SIT with 30 min case.

4.3 Summary of Gravity Makeup

Table 2 provides the definitions of core boiling, core uncover, fuel heatup and fuel failure and corresponding times for the base case.

The corresponding results for the other cases are summarized in Table 3.

These times are compared and summarized in Table 3 for the gravity makeups using CLP, SIFT, SIT with 30 min. feed, SIT with 1 hour feed and 2 SITs (30 min SIT and another SIT 1.5 hr). The gravity feed using CLP or SIFT is not effective for the LORHR event mitigation except for the inventory makeup during normal mid-loop operation.

Based on the study for the CLP makeup at the saturation time of 600 sec, the makeup is continued up to 15 minutes with average flow of 2 kg/s much smaller than 8.2 kg/s, which is the minimum makeup flow calculated at the same level of decay heat.

For SIT feed, core uncovery time is extended 4,470 sec (1 hr 15 min), 5,610 sec (1 hr 33 min) and 9,500 sec (2 hr 38 min) for 30 min SIT, 1 hr SIT and 2 SITs, respectively. The corresponding fuel cladding failure times are extended 4,250 sec (1 hr 10 min), 5,370 sec (1 hr 30 min) and 9,215 sec (2 hrs 34 min), respectively.

Table 2 Major Results for Base Case

Time to	**Description**	**Time (sec./hr)**
Core Boiling (t_{cb})	Time of incipient boiling at the top of core	423
Core Uncovery (t_{cu})	Time of complete voiding at upper plenum just above the core	6,795/1.89
Fuel Heatup (t_{hu})	Time to sharp increase of fuel cladding temperature	7,020/1.95
Fuel Failure (t_{ff})	Time to PCT > 1477 K	10,815/3.0

Table 3 Comparison of Results

Time (sec)	**Cases**				
	CLP	**SIFT**	**SIT (0.5)**	**SIT (1 hr)**	**2SIT**
t_{cb}	423	423	423	423	423
t_{cu}	6,855	6,890	11,265	12,405	16,295
t_{hu}	7,030	7,095	11,465	12,620	16,410
t_{ff}	10,675	10,805	15,065	16,185	20,030

5. Conclusion

From the LORHR event analysis, the effective means of gravity makeup for APR1400 to cope with this event concurrent loss of all AC power is determined as the gravity feed using SITs.

Other means for gravity makeup using CLP or SIFT, which are not designed to mitigate the LORHR event, are evaluated as not effective to the event due to the large flow resistances and the low elevation head to overcome the system pressure increase during the LORHR.

The use of one SIT and two SITs for the LORHR provides the core uncovery times as 3 hr 8 min and 4 hr 32 min extending 1 hr 15 min and 2 hr 38 min from the base case, respectively. And the times for fuel failure are extended from 3 hrs to 4 hr 11 min and 5 hr 34 min, respectively.

Using SITs as the makeup source for the LORHR, the sufficient time for operator action before core uncovery is provided and the fuel failure time for 2-SIT is sufficiently increased for APR1400.

REFERENCES

[1] NUREG/CR-5355, Rev. P4, "RELAP5/MOD3.3 Code Manual," Nuclear Systems Analysis Operations, Information Systems Laboratory Inc., October 2010.

[2] ANSI/ANS-5.1-2005, "Decay Heat Power in Light Water Reactors," ANS, April 2005.