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Analysis of Loss of RHRS in POSRV Open Case for ATLAS Mid-Loop Test Using MARS-KS Code

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1. Introduction

After the shutdown of pressurized water reactor (PWR) for refueling and maintenance outage, the core decay heat of reactor is removed through the residual heat removal system (RHRS). The reactor coolant level of the primary system is required to reduce to the mid-height of hot legs during the maintenance and inspection activities. The upper part of the primary system is filled by non-condensable gas such as air or nitrogen. This operational mode of the RHRS is termed as mid-loop (ML) operation. After the loss of the RHRS at ML operation, reflux condensation mechanism plays vital role in core cooling. In reflux condensation mode of PWR, steam produces in core, enters steam generator (SG) u-tubes, condenses and drains back through hot legs to the core.

In the loss of RHRS of PWR during ML operation, the safety of the reactor may be threatened severely by the boiling of coolant inventory if decay heat is not removed properly. The risk from low power and shutdown (LPSD) conditions is recognized for some time as to some extent comparable to full power risk, and among the LPSD sequences the loss of RHRS at ML conditions is the highest [1].

Many safety studies have been conducted for accident transients with full power operation of nuclear power plant (NPP) using MARS-KS system code but it is rare to find any specific and in-depth analysis by MARS-KS in case of the loss of RHRS transient in ML operation. Best estimate codes have initially been developed to simulate full power operation conditions, which are different from physical conditions of ML operation mode. It is necessary to assess the simulation of physical phenomena under transient in ML conditions by MARS-KS code and it is also important to make comparative analysis between the experimental result and the code calculation.

The main objectives of this study are to analyze the thermal hydraulic behavior after the loss of RHRS, to investigate the reflux-condensations characteristics in steam generator u-tubes in the presence of non-condensable gas, and to make comparative analysis between the MARS-KS calculation and the Advanced Thermal–Hydraulic Test Loop for Accident Simulation (ATLAS) ML test.

2. Overview of ATLAS Mid-Loop Test

ATLAS is a thermal-hydraulic integral effect test facility for evolutionary pressurized water reactors of advanced power reactor (APR1400) and optimized power reactor (OPR1000). The ATLAS has the same two-loop features as the APR1400 and the primary system consists of a reactor vessel, two hot legs, four cold legs, a pressurizer, four reactor coolant pumps, and two steam generators. Most of the safety injection features of APR1400 and OPR1000 are incorporated into the safety injection system of ATLAS. It is a 1/2-height, 1/144-area, 1/288-volume scales, full pressure, and full temperature scale of the APR1400 [2].

There were there ML tests conducted in ATLAS. ML test-01 and ML test-02 were conducted at atmospheric pressure condition while ML test-03 conducted on high pressure condition. In this study the ML test-01 and ML test-02 are analysed. The aim of these tests are to investigate whether the steam generators are capable of removing all residual heat generated from the core by reflux condensation mode.

In ATLAS ML tests, the primary system was filled by water up to the center line elevation of horizontal hot legs. The empty space of the reactor coolant system (RCS) was filled with air. Both steam generators have their secondary sides with 5 m full of water to remove the residual heat. Tests were conducted with the open case of pilot operated safety relief valve (POSRV) and main steam safety valve (MSSV). The residual thermal power of ML test-01 and ML test-02 were almost 129kW and 83.3kW respectively after the compensation of heat loss of ATLAS facility. The core decay power level was chosen in these tests on the basis of 0.3657% of full power at 96 hours after reactor shutdown [3].

The coolant was taken out at the bottom of hot leg-1 at mass flow rate of 1.5 kg/sec and cold water injected into the reactor vessel right hand side upper annulus with two inlet point with the mass flow rate of 0.75 kg/sec. The mass flow rate of coolant was decided on the basis of energy balance.

To conduct these ML tests, at first steady state condition is run with RHRS for 300 sec. At 300 sec, The RHRS is lost and the test begins and it ends when the cladding temperature starts to increase.

3. MARS-KS Simulation of ATLAS Mid-Loop Test

The MARS-KS code was developed by KAERI for a realistic multi-dimensional thermal-hydraulic system analysis of LWR transients which is based on the multi-dimensional code, COBRA-TF, and one-dimensional system code, RELAP5/MOD3.3.

The MARS-KS input model of ML operation of ATLAS has been obtained from the model at full power operation. The boundary conditions were modeled using the time dependent volumes. The RHR flow inlets and outlets are modeled by time dependent junctions connecting by time dependent volumes with reactor vessel right hand side upper annulus and hot leg-1 respectively. The openings of the POSRV and MSSV was modeled using valve connecting with time dependent volumes. The transient is simulated in this model by isolating the RHRS. The core power was kept constant during the steady state as well as during the transient simulation.

Table I: Initial condition of test and simulation

Parameter	ML Test-01		ML Test-02	
	Test	MARS-KS	Test	MARS-KS
Core power (kW)	129	129	83.3	83.3
Hot leg temperature in (K)				
Hot leg 1 (K)	350.68	348.48	345.94	342.83
Hot leg 2 (K)	348.25	350.50	345.28	347.35
Hot leg average (k)	349.46	349.49	345.61	345.09
Cold leg temperature (K)	326.31	328.81	318.21	329.97
SG secondary temperature riser (K)				
SG-1 (K)	317.18	317.46	301.10	302.18
SG-2 (K)	316.13	319.87	305.89	305.06
SG Average (K)	316.65	318.66	303.50	303.62
RCS Liquid level	Hot leg center point			
SG secondary side water level (m)	5	5	5	5
Feed-water flow	No feed water flow			
POSRV State	Open			
MSSV State	Open			
RCS system empty space filled	Air			
RCS pressure (N/m^2)	$1.05*10^5$	$1.05*10^5$	$1.08*10^5$	$1.04*10^5$
Secondary side pressure (N/m^2)	$1.013*10^5$	$1.013*10^5$	$1.013*10^5$	$1.013*10^5$
RHRS inlet mass flow rate (kg/sec)	0.75 0.75	0.75 0.75	0.75 0.75	0.75 0.75
RHRS outlet mass flow rate (Kg/sec)	1.5	1.5	1.5	1.5

After the accomplishment of the nodalization of the ATLAS MARS-KS model, a text input file describing the geometrical and thermal-hydraulic conditions of the nodalized volumes representing the flow path of various components in ATLAS, were made according to the steady state result of ML test. As long as the steady state value of simulation close to the steady state value of ML test, the MARS-KS steady state is re-calculated by the code. The steady state calculation was run for 10000 sec. The calculated steady state values obtained in MARS-KS calculations compared with the ATLAS ML experimental data are shown in table I which shows good agreement except the minor difference of cold leg temperature.

For the transient calculation, a text file describing the transient conditions of the loss of RHRS is made. After, the steady state calculation was conducted for 10000 sec, the transient calculation was started at 0 sec initiating by the isolation of RHRS. To observe the important thermal hydraulic phenomena, the transient is run for a longer time until the code automatically terminated the calculation.

4. Results

The results obtained in MARS-KS calculations follow the general behavior of ATLAS ML test specifically the progression of fluid temperature, RCS pressure, and liquid level with slight differences. Conversely, PZR water level is not well predicted by MARS-KS. Consequently, the higher temperature of RCS coolant and earlier heat up of claddings in MARS-KS is observed. The calculated and measured results of main thermal hydraulics parameters in the transient are summarized in table II. The graphs shown in this study are the comparison between the ML test-01 and simulation only.

Table II: Typical parameter of test and simulation

Parameter	ML Test-01		ML Test-02	
	Test	MARS-KS	Test	MARS-KS
Beginning of boiling (sec)	828	1121	2468	2000
Maximum RCS pressure (MPa)	0.245	0.224	0.251	0.233
Maximum PZR liquid level (m)	3.82	5.36	2.78	4.71
Beginning of core uncovery (sec)	1438	2713	12000	7602
Beginning of core heat up (sec)	11736	11049	17338	15268

After the loss of RHRS, the heat up of the liquid of RCS and the rise of temperature occurs due to decay heat. The pressure also increases and boiling begins in saturation condition. The figures 1, 2, and 3 show the temperature trend of hot legs, core heater, and steam generator secondary side respectively.

From the figure 1, it is clearly observed that coolant temperature sharply increased until saturation temperature, then it gradually increased for both case. At 12250s, the experimental temperature suddenly increases while calculated value shows stable behavior.

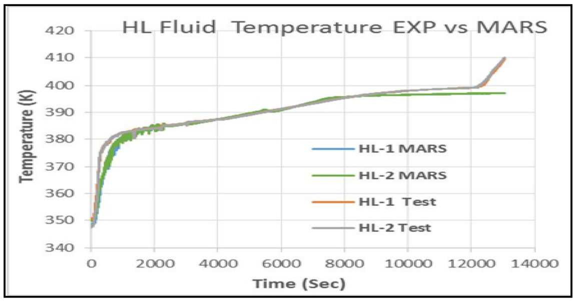

Fig. 1. Hot leg temperature

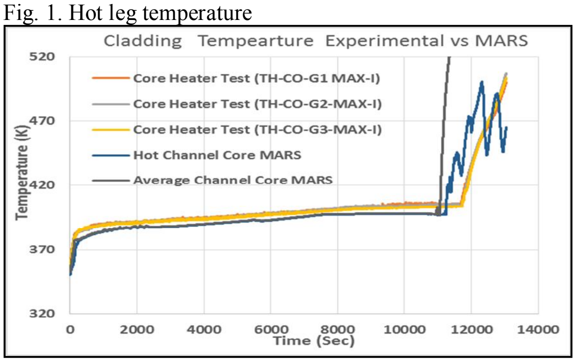

Fig. 2. Cladding temperature

The heating of coolant and metal mass of RCS occurs due to the buoyancy-driven natural circulation of liquid of the core. It is seen in figure 2 that the cladding temperature is slightly more than the calculated value all through the transient but overall behavior is agreed. At 11049 sect, the heat up of average channel core starts in calculation while in test it begins at 11736 sec.

The figure 3 demonstrates that temperature of secondary side of SG is almost constant in its initial value before the boiling of primary side. The core decay heat is consumed to heat up the primary side until the beginning of boiling. The fluid temperature of the riser of the SG1 and SG2 differs in both case.

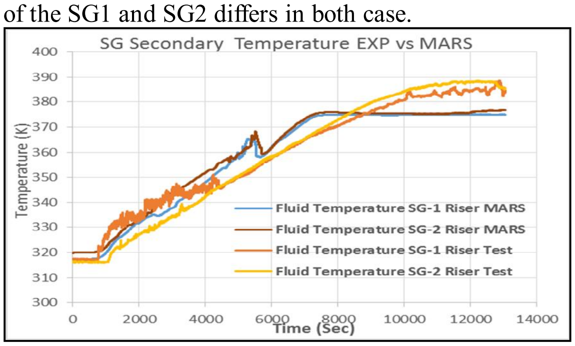

Fig. 3. Steam generator secondary side temperature

The evolution of pressure in hot legs by MARS-KS is similar with the test data which is displayed in figure 4. The maximum pressure of hot legs reached to 0.224 MPa in simulation while in test it is 0.245 MPa from atmospheric pressure. However, the pressure trend varies in the pressurizer (PZR) which may be the reasons of POSRV mass flow rate between the simulation and test. The pressure of hot leg is higher than the pressure of PZR in MARS-KS code because of the fully open of POSRV and the steam flow from core to the hot leg after the onset of boiling in core.

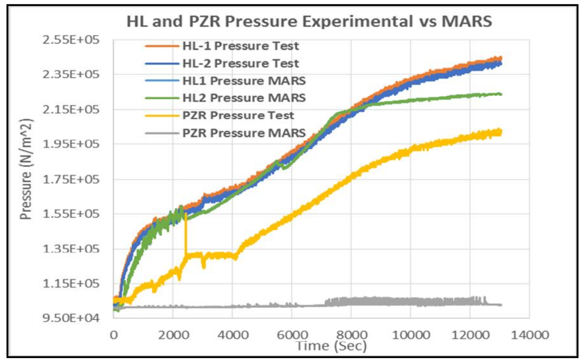

Fig. 4. Hot leg and pressurizer pressure

The collapsed liquid level of core, down-comer, hot legs, cold legs, intermediate legs slightly differs between the measured and calculated value but the liquid level of PZR differs largely. It means that MARS-KS predicts a larger amount of water enters into the PZR. The figures 5, 6 and 7 show the liquid level of core, PZR, and hot leg respectively.

After the beginning of boiling, the steam comes out and spreads to the RCS. The water level in the core shows sharp decrease in the early period of transient, according to the figure 5. The core uncovery begins around 1438 sec in test while at 2713 sec in MARS-KS. Active core level is considered 2.627m for the starting of core uncovery. The calculated collapsed liquid level of core slightly under predicts, consequently earlier core heat up begins in MARS-KS. In simulation, the down-comer water level decreases considerably after 8000 sec due to the sudden RCS pressure increase, later it steadily decrease due to equilibrium pressure of RCS. In the test, the down-comer level start to increase from 5690 sec to 7116 sec, after that it decreases steadily.

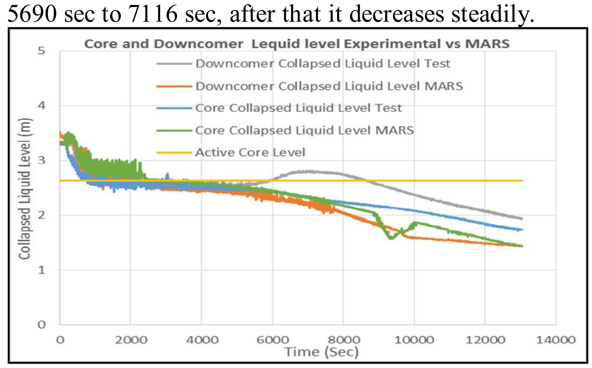

Fig. 5. Core and down-comer collapsed liquid level

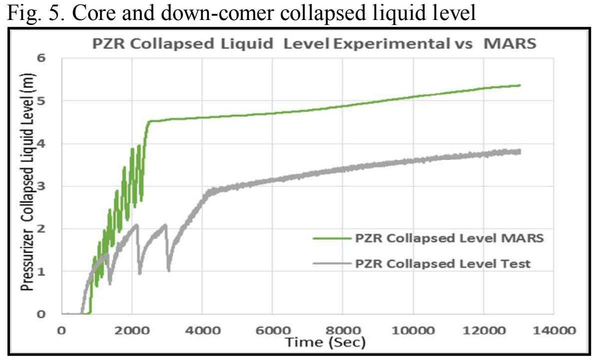

Fig. 6. Pressurizer collapsed liquid level

The high steam velocity through the surge line, cause water to be held up in the PZR. Water starts to enter into PZR almost at same time in both case but the liquid level of PZR of MARS-KS and test value shows discrepancy after the beginning of boiling. The PZR level calculated by MARS-KS presents a larger increase than the test after 2000 s according to figure 6. This means that more water is displaced towards PZR in simulation compare with the test. The water level in PZR were almost stable after 6000 s with slightly increasing trend in both case. After the stabilization of PZR level, value differs around 1.40m between the calculation and the test.

The collapsed level of HL becomes almost 0 m from 3247 sec to the end in MARS-KS but in test it becomes negative after 6000 sec which is shown in figure 7.

The behavior of fluid velocities of hot legs in SG side in MARS-KS calculation is shown in figure 8. Initially, liquid velocity shows upward trend but after 2425 s, it displays complete downward trend. Gas flows upward while liquid flows downward which is a counter current flow, occurs as a result of reflux condensation.

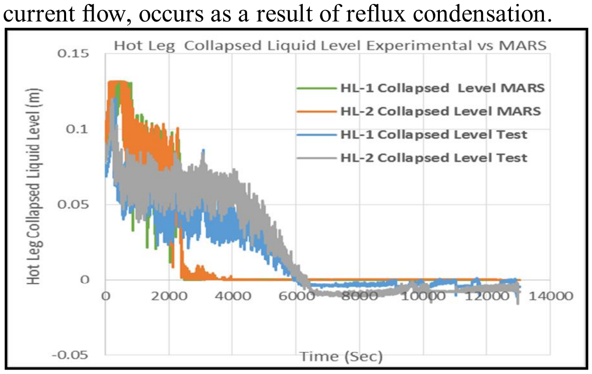

Fig. 7. Hot leg collapsed liquid level

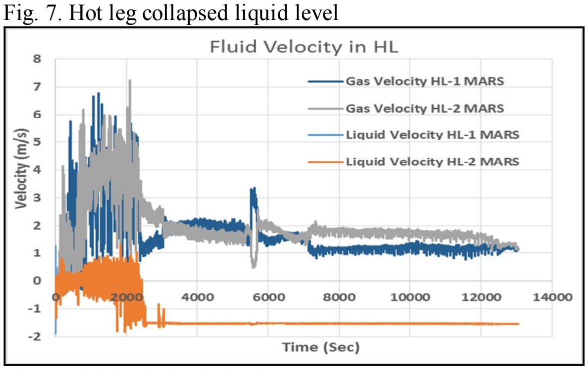

Fig. 8. Fluid velocity in hot leg

5. Conclusion

In order to study the thermal–hydraulics phenomena in the loss of RHRS in ML operation of PWR with the presence of air, this study focuses on the simulation of ATLAS ML test, by MARS-KS code. In general, the physical phenomena observed in the experiment are reproduced by the MARS-KS calculation. However, mass inventory distribution shows discrepancy particularly the PZR liquid level.

The simulation by RELAP5/Mod3.3 code, of E3.1 experiment conducted at the PKL facility in ML condition shows that PZR level calculated by RELAP5 was higher than the experimental value [4]. A comparison of test data with RELAP5 and TRACE simulations has also been performed for the PKL tests E3.1 and F2.2 run 2 on the loss of RHRS which shows that PZR water level was more than the test data in both case [5]. The geometrical configuration, decay power, and mid loop operation mode of PKL test are different form ATLAS test. So, careful consideration with these comparative justification is required.

In ML test-01, core uncovery and boiling begins earlier in experiment with the comparison to the calculation while in ML test-02 the opposite trend occurs due to the earlier boiling in experiment. Besides, the beginning of core heat up occurs earlier in ML test-01 than the ML test-02 for both in simulation and in test which shows agreement with the difference of core decay power between these two tests.

The foremost contribution of this work is the identification of main thermal hydraulics phenomena in ML operation of NPP with the evolution of time and to assess the capability of MARS-KS code in case of the loss of RHRS transient.

This study predicts that the over estimation of interfacial drag of two phases in surge line causes more liquid holdup in PZR by MARS-KS code which is the key reason of overall discrepancy with the test result. Besides, the counter current flow behaviors and the effects of non-condensable gas on condensation heat transfer in code may also be the sources of inconsistency. Finally, this study confirms that MARS-KS code is capable to analyze the transient of the loss of RHRS in ML operation of NPP.

Acknowledgements

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