Analysis of Uncontrolled Level Drop and Increase during Mid-Loop Operation

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1. Introduction

Reduced inventory or mid-loop operation may be adopted by utilities for increasing the availability of Pressurized Water Reactors (PWRs). If mid-loop operation has to be used for the nozzle dam installation and removal for the Steam Generator (SG) inspection and maintenance, or Reactor Coolant Pump (RCP) seal replacement during refueling outage, it shall be demonstrated that functionality of residual heat removal systems is not impaired [1].

In EU-APR, which is a modified design of the APR1400 to penetrate the European nuclear market, the Mid-loop Level Control System (MLCS) has been developed to provide an automatic control of Reactor Coolant System (RCS) water inventory by continuously monitoring the RCS loop level and controlling the charging and letdown flow rates [2]. This study presents inventory makeup features and the MLCS capability, with emphasis on the residual heat removal, against uncontrolled level drop and increase during mid-loop operation.

2. Mid-loop Level Control System Design

2.1 Ground rules

The RCS loop level limitation function shall monitor continuously the loop level during mid-loop operation. Ground rules for the associated design are as follows:

- The RCS loop level limitation function makes sure that the minimum and maximum admissible water levels are kept within the control range in case of transients. This limitation function acts when an overshoot of the control band limit occurs.
- The RCS loop level limitation function considers the water level required to protect the shutdown cooling pumps from cavitation during the mid-loop operation.
- Filling the loops may interrupt the flow area for the purge gas in the loop and the necessary free water surface for removal of noble gas. This could endanger personnel working in the SG heads and potentially discharge coolant to the containment via open SG manways. This limitation function also prevents inadvertent filling of the loops.
- The RCS loop level limitation function closes fully the reducing points of the Chemical and Volume Control System (CVCS) letdown line through the shutdown cooling purification paths when the RCS water level falls below a dedicated threshold that is below the lower control band limit of the RCS loop level control function. This limitation function fully opens the reducing points to increase the letdown flow rate when the water level exceeds a dedicated threshold above the upper control band limit of the RCS loop level control function.
- The RCS loop level limitation function is disabled beyond its specified operating range in order to exclude the occurrence of inadvertent actuation signals.

2.2 Inventory Control

As shown in Figure 1, the MLCS performs multiple functions such as the control, the limitations and the protections and controls the safety class components such as safety injection pumps, shutdown cooling pumps and related valves. During the mid-loop operation, the RCS loop level is maintained by controlling the CVCS charging control valves and the letdown valves to ensure that there is sufficient RCS water inventory for core cooling while the minimum required shutdown cooling pump is operated to appropriately remove the core residual heat.

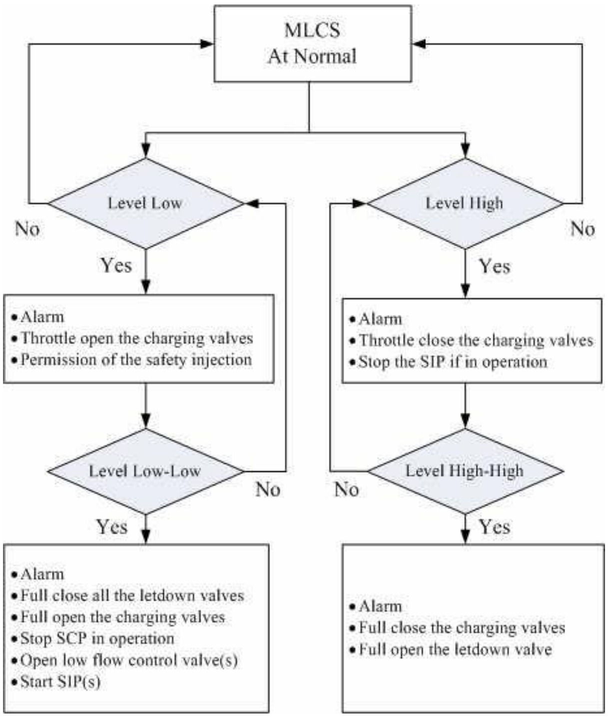

Figure 1. Mid-loop Level Signals and Control Logic

2.3 Makeup System Capabilities

The charging system consists of three centrifugal charging pumps and two charging flow control valves, which is connected to the RCS by one charging nozzle. Each charging pump has the capacity of about 16 kg/sec.

During the mid-loop operation, the letdown flow path is formed through the shutdown cooling purification line, which has the capacity of about 9.4~18.8 kg/sec.

The safety injection system consists of four independent trains which are connected to their own direct injection nozzles on the reactor vessel (RV) wall, and each train has maximum capacity of 70.2 kg/sec. During the mid-loop operation, however, the safety injection flow rate of each train is limited to about 9.4 kg/sec through the safety injection low flow control line.

3. Analysis and Results

This section considers the countermeasures that are possible in the event of failure of the loop level controls.

One of the most probable events is accidental draining of the RCS due to malfunction of the CVCS during the mid-loop operation. Another case to be taken into account is the small break Loss of Coolant Accident (LOCA) during shutdown conditions with a depressurized RCS to the atmospheric pressure.

The mitigation capability against the level increasing event also has to be considered. The most significant level increase event can be caused by an inadvertent operation of a safety injection train when the letdown valve is closed.

3.1 Uncontrolled level drop event

During a mid-loop operation, an uncontrolled level drop of RCS can be initiated when the letdown valves are fully opened. Inadvertent actuation of letdown isolation valves to fully open decreases the RCS level, which can cause a loss of shutdown cooling. The RCS inventory makeup capability is considered to prevent loss of shutdown cooling due to an air entraining into the shutdown cooling suction line.

The time to boil (t_b) can be calculated as follows:

$$t_b = \frac{\rho V c_p (T_{sat} - T_w)}{Q_d}$$

where,
- c_p = the specific heat
- Q_d = the decay heat
- T_{sat} = the saturation temperature
- T_w = the initial coolant temperature
- V = the effective volume of RCS
- ρ = the fluid density

The time to core uncovery (t_u) can be calculated as follows:

$$t_u = \frac{\rho V[(h_{g,sat} - h_{f,sat}) + (h_{f,sat} - h_f)]}{Q_d}$$

where,
- h_f = the initial liquid enthalpy
- $h_{g,sat}$ = the enthalpy of saturated vapor
- $h_{f,sat}$ = the enthalpy of saturated liquid
- T_w = the initial coolant temperature
- Q_d = the decay heat
- V = the effective volume of RCS
- ρ = the fluid density

In order to estimate the makeup flow rate necessary to keep the core covered during a loss of residual heat removal event, two different calculations were performed to prevent the core from either boiling or uncovery. The steady state energy balance relation was used to estimate the mass flow rate required to prevent the core from boiling or to replace water boiled off at a given decay heat power. The energy balance equation is as follows:

$$\dot{m} = Q(t)/\Delta h$$

where,
- $\dot{m}$ = the mass flow rate or the steaming rate in the core,
- $Q(t)$ = the decay heat power
- Δh = the enthalpy change between the inlet and outlet of RV

The evaluations for times reaching a core boiling and uncovery were performed by using RELAP5/MOD3 code, with assumptions below.

- The initial water level is at the middle of the hot leg pipes.
- The initial reactor coolant temperature is 57 ℃.
- The decay heat power is at four days after the reactor shutdown, which is evaluated to be about 0.45% of full power (18 MW).
- The temperature of fluid is distributed homogeneously.
- The effect of solid structures in the RCS is neglected.

During mid-loop operation at four days after shutdown, the times to core boiling and core uncovery were calculated to be 450 seconds and 4,900 seconds, respectively. The minimum makeup flow rates required to prevent the core from boiling and uncovery were calculated to be 78.8 kg/sec and 7.9 kg/sec, respectively.

The makeup capability through two safety injection trains is 18.8 kg/sec which is the same as the maximum letdown flow rate. The charging flow rate is 9.6 kg/sec. Therefore, the charging flow is sufficient to compensate for the boil-off rate to prevent the core uncovery.

3.2 Uncontrolled level increase event

During a mid-loop operation, an over-filling of RCS can be initiated when the letdown isolation valves are closed or a safety injection train is inadvertently operated.

To calculate the time to the high and high-high level set-points, the level variation speed is evaluated with the maximum safety injection flow rate of approximately 9.4 kg/sec through the safety injection bypass line and the volume per unit elevation. The times to reach the high and high-high level set-points are approximately 407 seconds and 642 seconds, respectively.

With the level control by the charging and letdown balancing, the mid-loop level control system can cope with an inadvertent safety injection through the safety injection low flow control line since the safety injection flow rate is within the charging and letdown flow balancing capability.

4. Conclusions

In EU-APR, the MLCS has been designed to control automatically the RCS level during the mid-loop operation. This study was performed to assure residual heat removal during mid-loop operation.

The uncontrolled level drop due to full open of the letdown valve can be compensated by the safety injection capacity with two train operations and the charging flow rate. A loss of shutdown cooling is also manageable by the makeup capacity of mid-loop level control system by injecting the borated water through the safety injection trains. The level increasing event is controllable by increasing the letdown flow rate and decreasing the charging flow rate.

We can conclude that the MLCS is capable of inventory control by each safety injection line, which is sufficient enough to prevent the core from uncover, as summarized in Table I.

Table I: Performance Evaluation Summary

Event	Rate of change (kg/sec)	Control capacity (kg/sec)	Remarks
Uncontrolled Level Drop	18.8+7.9	18.8+9.6	Acceptable
Loss of Shutdown Cooling	7.9*	9.4**	Acceptable
Uncontrolled Level Increase	18.8	9.6+9.4	Acceptable

* Required flow rate for core uncover
** Minimum flow rate by one safety injection train

REFERENCES

[1] “European Utility Requirement document,” Vol. 2 Chapter 2.8 Section 3.3.1.3.2: System arrangement and mid-loop operation, Rev. D, October 2012.
[2] W.S. Yang and Y.S. Kim, “Design of RCS Level Control System for Mid-loop operation according to the European Requirements”, Proceedings of Korean Society for Energy Spring Meeting 2013