Transient Analysis of CVCS Malfunction in Large Passive PWR

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Abstract. The present work focuses on a simulation of increase of coolant inventory due to malfunction of chemical and volume control system (CVCS) in advance passive pressure water reactor 1000 (AP1000) operating at a 102% nominal power before transient start-up. The objective is to verify if this transient may induce any over pressure in the reactor coolant pressure boundary due to inadequate residual heat removal. RELAP5 system code was used to simulate the transient and the simulation result was compared with the simulation result by LOFTRAN code. The RELAP5 simulation result is well comparable with the simulation result by LOFTRAN and this transient does not endanger the AP1000 pressure boundary system.

1. Introduction
During normal operation of the large pressurized water reactor (PWR), the residual heat is adequately removed by forced convection either by reactor cooling system or by normal residual heat removal system. Special safety engineering features are normally incorporated into the design to ensure a safeguard of the integrity during anticipated transient and severe postulated accident.

In case of large passive PWR, a safety feature of concern is a transient that result in increase of the reactor coolant inventory due to malfunction of the chemical and volume control system CVCS [1].

Even though during the design of large passive PWR, the passive residual heat removal system (PRHRs) has been incorporated into design [2-4], however, the demonstration of the safe behavior of large passive PWR under transient due to malfunction of CVCS must be shown.

The objective of the present work is to investigate the behavior of the reactor coolant pressure boundary during an increase of the reactor coolant inventory due to malfunction of CVCS. Under these conditions, the reactor coolant system is at a lower average temperature, higher pressure, and a higher pressurizer level at the time the reactor trip signal is generated. These conditions produce a greater volume of higher density water and, thus, a larger reactor coolant system mass at the time of the reactor trip signal. In addition, at lower reactor coolant system average temperature, the PRHRs is less effective in removing decay heat.

This transient scenario has been simulated by applying the RELAP5/SCDAPSIM/Mod 3.4 code [5] system to the AP1000 [6] design with operating at 102% nominal power. The simulation result is also compared with the results of the LOFTRAN code [7,8].
2. Nodalization
The AP1000 reactor [6] is representative of large passive PWR. The AP1000 has core nominal power of 3400 MWth. The reactor has two reactor cooling system (RCS) loops and has a passive core cooling safety system (PXS) to mitigate transient and accident events.

The AP1000 RELAP model that was developed by the author [9-11] was modified to represent the primary cooling system and the boundary conditions in order to permit the simulation of the CVCS malfunction. Figure 1 shows a view of the nodalization used in the simulation. In the RELAP5 [12] model, the AP1000 RCS and passive core cooling safety system are modeled by using various kinds of hydrodynamic component including Volumes, Pipes, Branches, Junctions, Valves, Separators, and Pumps. The detail AP1000 RELAP model description can be found in reference [9-11].

In order to simulate AP1000 CVCS malfunction, a model or CVCS was added to the nodalization. The CVCS is modeled by a time dependent volume to represent CVCS water temperature and boron concentration. The CVCS pump injection flow rate is modeled by a time dependent junction.

![Figure 1. RELAP5/SCDAPSIM AP1000 Plant model for CVCS malfunction [9-11]](image-url)

3. Initial Condition and Transient Scenario
In the AP1000, the increase of reactor coolant system coolant inventory may be due to the unplanned operation of one or both of the chemical and volume control system pumps or by the closure of the letdown path. In this study, the initial condition and accident scenario are similar to that used in the AP1000 design control document, chapter 15 [8]. At steady state, the initial reactor power is assumed to be two percent above nominal. The initial pressurizer pressure is assumed to be 344.75 kPa more than nominal value and the reactor coolant system average temperature is assumed to be 3.61°C more than nominal value.
After 10 seconds at steady state, both of the chemical and volume control system pumps unintentionally begin providing flow at a boron concentration slightly higher than that of the reactor coolant system. The high pressurizer pressure reactor trip is prevented due to the non-safety-related pressurizer spray is assumed to be available. Upon receiving an “S” signal, the chemical and volume control system pumps are isolated and the core makeup tanks (CMT) start injecting 3400 ppm borated water.

4. Results and Discussion

4.1. Steady State Condition

A steady state input deck for the RELAP5 code was built to provide the initial conditions of the transient scenario. This input deck was managed by introducing a time-dependent volume and a time-dependent junction with control system so that the calculated operational parameters can be achieved with the requirement value of initial condition.

In this approach, they were set to the required physical values for: core power, average reactor coolant temperature, pressurizer pressure and level, steam produced, just to name a few. All the selected thermal-hydraulic parameters values were found in [8,13]. This stationary transient was run for 1000 seconds to verify that the calculated conditions were steady and the actual initial conditions of the simulation were achieved. After the desired steady-state conditions were achieved, some of the time-dependent components were removed to verify the stability of the modeling. Table 1 shows the comparison between the RELAP5 thermal-hydraulic parameters values obtained in stationary simulation for initial condition of CVCS malfunction and the nominal AP1000 thermal-hydraulic parameters. It can be seen from the table that the calculated values by RELAP5 were in good agreement with the requirement of the initial value for the simulation [8]. The core power is 3468.02 MWth equal to 102 percent of its nominal value. The RCS pressure is around 344.75 kPa above its nominal values. The average reactor coolant temperature is 578.01 K, which is around 3.61°C higher than its nominal value. The restart file generated by this run has been used as initial condition for the transient simulation.

Table 1. Steady state calculated of AP1000 for CVCS malfunction obtained by the RELAP5

| Parameters                        | AP1000 Nominal value [13] | RELAP5 value  |
|-----------------------------------|----------------------------|---------------|
| Core thermal power, MWth          | 3400.00                    | 3468.02       |
| RCS pressure, MPa(abs)            | 15.51                      | 15.85         |
| Vessel inlet temperature, K       | 553.82                     | 555.20        |
| Vessel outlet temperature, K      | 594.26                     | 600.82        |
| Vessel average temperature, K     | 574.04                     | 578.01        |
| Primary coolant flow rate, kg/s   | 14300.00                   | 14307.90      |
| Pressurized steam volume, m³      | 31.14                      | 31.19         |
| Steam flow per SG, kg/s           | 944.36                     | 963.14        |
| Steam pressure, MPa (abs)         | 5.76                       | 5.76          |
| Feedwater temperature, K          | 499.82                     | 499.82        |

4.2. CVCS Malfunction Conditions

The result of the simulation will be divided into two stages. The first stage is the period from the starting of the transient until reactor has been scrambled at 1098 seconds. The second stage is the period after reactor has been scrambled until the PRHR heat removal capacity over the reactor decay heat.

4.2.1. The first stage. After 10 seconds from steady state, the CVCS started to inject the borated water to the reactor cooling system. The mass flow rate of CVCS injection is about 12 kg / sec as shown in Figure 2. The flow rate is equivalent to the sum of nominal flow of the both CVCS pumps. In this simulation, the CVCS water injection rate was treated as boundary conditions of the RCS and it used to reproduce the events reported on the AP1000 safety design document [4]. Figure 3 shows the effect
of boron insertion to the reactor core power. The boron insertion has been simulated as a negative reactivity insertion. The reactor core power decreased as boron from the CVCS accumulated in the RCS. At the beginning of transient, the reactor was operated at 102% of nominal power and the power decreased to about 83% of nominal just before reactor has been scrammed

![CVCS Flow Rate Transient](image1.png)

**Figure 2. CVCS Flow Rate Transient**

![Core Nuclear Power Transient](image2.png)

**Figure 3. Core Nuclear Power Transient**
The decreasing of the core power results in the reducing the rate of steam production at the steam generator. To keep the power generation continued, the turbine valve opens fully so that the steam supply to the turbine remains fulfilled. The opening of turbine valves has an effect on reducing the vapor pressure of steam generator as shown in Figure 4. The decreasing of steam pressure in the steam generator results in the increasing the heat removal from the primary side to the secondary side (see Figures 5.a and 5.b). This situation was continued until a low average coolant temperature reached that produce a reactor signal trip. In this simulation the reactor was tripped after 1098 seconds from the start of CVCS water injection. During the injection period, the pressure increase of pressurizer due to the addition of water volume from CVCS is compensated by the operation of spray pressurizer. Before the reactor has been stopped, the pressurizer pressure tends to be stable as it is depicted in Figure 6. However, the excessive heat removal by secondary side of the steam generator causes a decline in the primary coolant temperature and subsequently causes a shrinking of the volume of water in the pressurizer as it can be seen Figure 7. This shrinking causes a decreasing pressure on the pressurizer as shown in Figure 6.
4.2.2. The second stage.

Figure 3 shows that the reactor power decreased rapidly after the fission reaction has been scammed. This power decrease leads to further cooling of the reactor coolant system (see Figures 5.a and 5.b). As explained in the transient scenario, the CVCS injection is isolated after the reactor has been scammed as it can be seen in Figure 2. The main feed water lines and the steam lines of the steam generator are also isolated. This isolation made steam accumulated in the steam generator and consequently increases steam generator pressure (see Figure 4). Upon the CMT valve is opened then CMT starts to inject cool water into the primary side of RCS. The rate of CMT injection can be seen in Figure 8. The CMT injection rate is at maximum at the beginning of injection; it is occurred due to the large hydrostatic pressure difference between the CMT pressure and Pressurizer pressure. In the long term, this pressure difference decreases due to the water injected from the CMT increases the water volume in the pressurizer (see Figure 7) and pushes the steam chamber at the top of the pressurizer and eventually increase the pressurizer pressure to reach the setting point for the opening of safety valve (see Figure 6). Following the opening CMT valve, 5 seconds later the PRHR line valve starting to open. Figure 9 shows the heat removal capability of PRHR compared with power generation due to decay heat inside the core. At the beginning of the operation, PRHR is able to remove the heat with a considerable high capability of about 1.7% of AP1000 core rated power. This is occurred because of the large temperature difference between the temperature of the primary cooling system water passing through the inside of the PRHR heat exchanger and the water temperature inside the IRWST pool. After a while the PRHR heat removal ability decreases as the primary coolant system cools down due to a lower-temperature CMT water injection than the temperature of the primary coolant system. In addition, the water temperatures in IRWST pool is increased because absorbing heat from the primary cooling system through a PRHR heat exchanger that further decreases the temperature difference between the primary cooling system and the water in the IRWST pool. The temperature of the reactor coolant system is increasing because the heat removal capability by PRHR from the reactor coolant system is still lower than that of heat transferred from the core to the primary cooling system until the end of CMT water injection to the primary cooling system. After that the heat removal capability of PRHR increases to exceed the power generation of core decay heat. As a result the temperature of the reactor coolant system decreases and results in shrinkage of the water at the pressurizer and eventually decreases the pressure of the pressurizer as shown in Figure 4. The opening of the PRHR valve allows for the natural circulation of water in the reactor coolant system in which this flow is affected by heat transfer capability in the PRHR. Initially PRHR is able to move large quantities of heat (see Figure 9), this results in a cooling water flow from inside the PRHR tube through the opening valve with a high flow rate (120 kg / sec) as shown in Figure 10. In the beginning, the PRHR heat removal capability was decrease and later on it is slightly increase; it also affects the primary coolant flow rate through PRHR.
The results of the transient simulation due to the failure of CVCS on AP1000 shows that the system response, in this case the primary system pressure, secondary system pressure, the increase of water volume in the pressurizer, the flow rate of CMT injection, the coolant flow rate through PRHR and PRHR heat removal capability, has similar trend with the result of LOFTRAN code which is reported in the AP1000 design document [8]. However, the RELAP5 has over predict on the mass flow rate of passive system (i.e. CMT and PRHR) at the starting of the system; it may be due to the different values in the k-loss factors for piping system of passive system that has been use in the RELAP5 and LOFTRAN simulations

Based on the simulation results it can be seen that this transient is not induce the over pressure in the reactor coolant pressure boundary of AP1000. The primary and secondary cooling system pressures are still below 110% of design pressure. In addition, the trend of both system pressures is decreasing in the long term.

5. Conclusion
The transient simulation of CVCS malfunction in AP1000 has been performed using RELAP5 code. The important parameters predicted by RELAP5 code and those by LOFTRAN code showed in good agreement. The AP1000 pressure system boundary is not endangered by CVCS malfunction that result in increase of reactor coolant inventory.
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