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Analysis of Thermal-Hydraulics Parameters During Steam Generator Tube Rupture Event of VVER-1200 NPP Using PCTRAN Simulator

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Abstract: The overall performance of steam generators plays a significant role in ensuring the safety of a nuclear power plant (NPP) operation. The analysis of thermal-hydraulic parameters during a steam generator tube rupture (SGTR) event of VVER-1200 NPP is conducted by applying the personal computer transient analyzer (PCTRAN) simulator. Four cases, namely, 25%, 50%, 75% and 100% of one tube rupture in two steam generators with the concurrent loss of AC power have been performed. Among the four cases, major variation in time was not observed for the occurrence of the reactor scram, reactor coolant pump trip, main feed-water pump trip, and turbine trip. The pressure and the temperature of the reactor coolant system (RCS) increase rapidly to a peak value due to event initiation, and drop promptly after the reactor scram. The stabilized pressure and temperature of the RCS are higher for the smaller break size of the SGTR. The secondary pressure of the steam generator is also increased to a peak value, followed by an increasing and decreasing trend, in turn, due to the repeated opening and closing of safety relief valves of the steam generators. The liquid level of the pressurizer is increased rapidly due to the liquid surge towards the pressurizer after the event and it is stabilized after the opening of the safety relief valve. The stabilized liquid level of the pressurizer and the steam generator is higher for the smaller break size of the SGTR. The earlier emergency core coolant injection to the reactor was required for the larger break size of the SGTR. There is no increase in the peak cladding temperature and the peak fuel temperature during the calculation period for all these cases. The results of this study provide a valuable understanding of SGTR events with the concurrent loss of AC power for the PCTRAN model of the VVER-1200 NPP.

Keywords: Nuclear power plant; PCTRAN; Steam generator tube rupture; Thermal-hydraulics; VVER-1200.

1. INTRODUCTION

The reliable performance of a steam generator plays an important role in ensuring safety during the operation of a pressurized water reactor. The analysis of a steam generator tube rupture (SGTR) event is very important to the safety viewpoint of a nuclear power plant (NPP) [1]. An SGTR event can cause a direct flow of coolant from the high-pressure reactor coolant system (RCS) to the low-pressure secondary system [2]. The SGTR event can contaminate the secondary system with the release of radiological products into the environment and it has been classified as a design-basis event for a pressurized water reactor [3]. A number of SGTR events have occurred during the operation of pressurized water reactors [4] and the progress of this event in an NPP depends on the availability of the safety systems and proper actions of the operators [5].

The personal computer transient analyzer (PCTRAN) is a product of Micro-Simulation Technology Inc., which can perform transient and accident simulation of NPP on a personal computer [6]. The investigation of thermal-hydraulic parameters of different hypothetical accidents of VVER-1200 NPP by applying PCTRAN simulator was conducted, namely, the loss of coolant accident with and without emergency core cooling system (ECCS) [7], the large-break loss of coolant accident [8], the loss of coolant accident with the loss of off-site power [9], the loss of normal feedwater flow, the SGTR event, and the loss of coolant accident [10], the inadvertent control rod withdrawal accident [11], a steam-line break accident [12], and an SGTR event [13], the failure event of AC power [14], and turbine trip concurrent with anticipated transient without scram [15].

The PCTRAN simulation was performed only for a single tube rupture in one steam generator of the VVER-1200 and the analysis was conducted [10, 13]. However, the analysis of different break sizes of tube rupture of two steam generators with the concurrent loss of off-site power has not been published yet in the available literature by applying the PCTRAN simulator for VVER-1200. It is necessary to observe the behaviors of thermal-hydraulic parameters comprehensively during an SGTR event of both steam generators using the PCTRAN simulator. Thus, the main objectives of this study are to analyze the plant response and the behavior of thermal-hydraulics parameters during the SGTR event of VVER-1200 NPP by applying the PCTRAN simulator.

2. STEAM GENERATOR OF VVER-1200 NPP AND PCTRAN SIMULATOR

The VVER-1200 pressurized water reactor is a Generation III+ NPP with a thermal capacity of 3200 MWth and a net electrical capacity of 1200 MWe [16]. The VVER-1200 RCS comprises a reactor pressure vessel, a pressurizer, and four circulation loops consisting of a steam generator, reactor coolant pump, a hot leg, and a cold leg in each loop. The RCS removes heat from the reactor by circulating coolant in a closed-loop, and the heat produced in the core is transferred to the secondary side through the steam generator [17]. The VVER-1200 NPP has a set of active and passive safety systems [18].

The steam generator employed in the VVER-1200 is the PGV-1000 MKP type, which comprises a steam generator, steam header, supports, shock absorbers, one and two-chamber surge tanks, embedded components for supports, and shock absorbers. The steam generator is a single-vessel heat exchanger of horizontal type with submerged heat-transfer surface and it consists of a vessel with different-purpose nozzles, a heat-exchange bundle with fastener and spacer components, primary coolant collectors, feed-water supply and distribution systems, emergency feed-water supply and distribution systems, distribution perforated plate, submerged perforated plate, and chemicals feeder [17].

The saturated steam produced in steam generator is flown through the holes of the perforated sheet submerged below the evaporation surface and the steam is dried and flown to the perforated distribution sheet in the upper part of the steam generator and the steam is entered into the steam header, from where it enters the steam lines. The water circulation on the secondary side of the steam generator is natural and the feed water is flowed into the feed-water distribution header of the steam generator. The heat transfer surface of the steam generator consists of 10978 stainless steel tubes of 16 mm diameter and 1.5 mm wall thickness. The heat exchange tubes are structured in a U-shaped bundle, which slopes downwards and the tubes are mounted by welding the ends to the inside surfaces of the main coolant inlet and outlet. The main steam line and the passive heat removal system pipe are connected to the steam header, located above the steam generator [18].

The PCTRAN model for the VVER-1200 model is available for transient and accident analysis. In the PCTRAN, a high-resolution color mimic displays the status of various parameters of the VVER-1200 NPP model [19]. The major advantage of the PCTRAN is the windows-based graphical user interfaces, which allow users interactions with the simulation software through the direct manipulation of the graphical elements [20]. In this study, a demo version 1.2.0 of the PCTRAN model of the VVER-1200 NPP is used, which provides the accident scenario for 300 sec. The snapshot of the PCTRAN model of the VVER-1200 NPP is shown in Figure 1 [19].

As shown in Figure 1, the PCTRAN model of VVER-1200 NPP has a thermal output of 3200 MWth, and it consists of two loops of RCS, with a reactor pressure vessel, a pressurizer, two steam generators, two hot legs, two cold legs, two reactor coolant pumps, ECCS, the low-pressure injection system, feed and bleed water system, accumulator, various safety valves and components of the NPP [19]. The components like pumps, valves indicating red-colored are in operation and white-colored are closed in the mimic, which can be switched on or off by clicking on the interactive display [7].

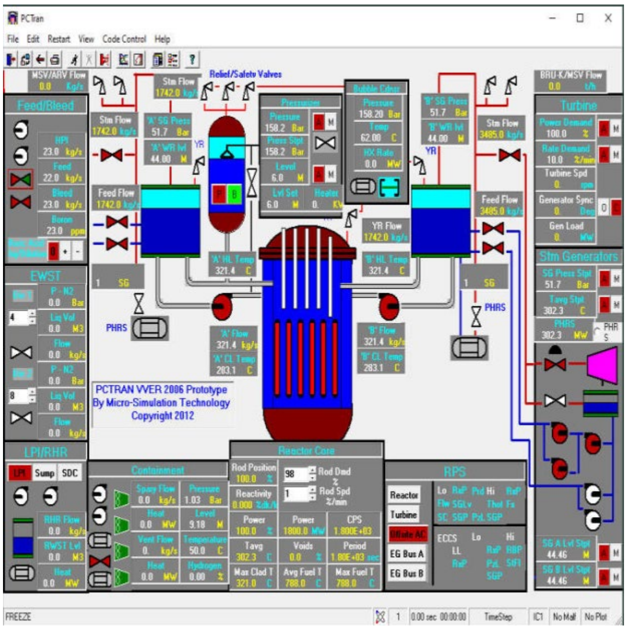

Figure 1. The snapshot of the PCTRAN model of the VVER-1200 NPP

Table 1. Thermal-hydraulic parameters of PCTRAN model of VVER-1200 NPP in steady-state condition

Parameter	PCTRAN Value
Reactor thermal power	3200 MWth
RCS pressure	162.0 bar
Pressure at steam generator	74.0 bar
Average primary coolant temperature	313 °C
Average primary coolant flow rate	17277.7 kg/s
Cold leg temperature	298.03 °C
Hot leg temperature	329.08 °C
Maximum cladding temperature	610.8 °C
Maximum fuel temperature	1800 °C
Main feed water temperature	298 °C

Table 2. Sequence of events

Events	25% (Case 1)	50% (Case 2)	75% (Case 3)	100% (Case 4)
Initiation of SGTR with loss of AC power	10	10	10	10
Reactor coolant pump trip	12	12	12	12
Main feedwater pump trip	12	12	12	12
Turbine trip	12.5	12.5	12.5	12.5
Opening of pressurizer safety relief valve 1	20	20	20	20
Opening of pressurizer safety relief valve 2	20.5	20.5	21	21
Opening of steam generator safety relief valve 1	20	20	20	20
Opening of steam generator safety relief valve 2	25	24.5	24.5	24.5
Closing of pressurizer safety relief valve 2	28.5	28.0	28.0	27.5
Closing of pressurizer safety relief valve 1	29	28.5	28.5	28
Reactor scram	30	29.5	29.5	29.5
Starting of diesel generator A	71	71	71	71
Starting of turbine driven auxiliary feedwater pump-1 and pump 2	71.5	71.5	71.5	71.5
End of Calculation	300	300	300	300

3. PCTRAN SIMULATION OF VVER-1200 NPP MODE

3.1 Steady-State Calculation

The PCTRAN simulator has a few preloaded initial conditions. In this study, the initial condition was selected as 100% full power at the beginning of the cycle. It is important to run the PCTRAN simulator to reach a stable condition before the initiation of the accident. After choosing the initial condition, the malfunction was initiated as the SGTR accident with the loss of AC power, which becomes active after 10 seconds of the normal operation of VVER-1200 NPP at the PCTRAN simulator. The most important thermal-hydraulic parameters of the steady-state condition of the PCTRAN model of VVER-1200 NPP during normal operation are shown in Table 1. It is mentioned that the value of steady-state parameters is similar for all four cases of SGTR event with the loss of AC power for the PCTRAN model of VVER-1200 NPP.

3.2 Steady-State Calculation

In this study, four hypothetical cases are designed as the simultaneous occurrence of the SGTR in both steam generators with the loss of AC power after normal operation of 10 seconds, by using the PCTRAN model of VVER-1200 NPP. Four cases namely, 25% (Case 1), 50% (Case 2), 75% (Case 3), and 100% (Case 4) of one tube rupture in two steam generators with the concurrent loss of AC power of PCTRAN model of VVER-1200 NPP have been performed in this study.

After the steady-state run for 10 seconds, the transient began at PCTRAN model VVER-1200 NPP of SGTR of 25%, 50%, 75%, and 100% full tube rupture in both steam generators with the occurrence of loss of AC power. The transient calculation was carried out for 300 seconds for all the cases. The major sequence of events during the transient calculation of the PCTRAN model of the VVER-1200 NPP is summarized in Table 2, where the unit of the occurring event time is seconds. As shown in Table 2, there is no significant variation of time for the occurrence of different events among the four cases. The reason for this trivial variation of time on the parameters among different cases of the SGTR event is the occurrence of the loss of AC power at the same time for all four cases. After the occurrence of reactor scram, the steam generator safety relief valve 1 and steam generator safety relief valve 2 changed their positions intermittently as closed and opened positions for all the cases.

4. RESULTS

The RCS pressure and the RCS average temperature are shown in Figure 2 and Figure 3, respectively. As shown in Figure 2, after the initiation of SGTR, the primary pressure increased rapidly to a peak value of 175.60 bar, 175.13 bar, 175.13 bar, and

174.67 bar at 25 sec for Case 1, 2, 3, and 4 respectively. As shown in Figure 3, the average temperature of RCS also shows a peak value of 332.90 °C for all the cases at 25 sec, which agrees well with the trend of RCS pressure. Naturally, reactor pressure and temperature must decrease after the initiation of SGTR but it increases according to Figure 2 and Figure 3. Although the safety relief valve 1 of the pressurizer opened at 20 sec for all the cases, the safety relief valve 2 of the pressurizer opened at 20.5 sec for Case 1 and Case 2, and at 21 sec for Case 3 and Case 4 but the reactor pressure and temperature continued to increase. The reason for the increase of the reactor pressure and temperature after the initiation of the SGTR event can be attributed due to the simultaneous loss of AC power with the SGTR and due to the occurrence of reactor coolant pump trip, main feed-water pump trip, and turbine trip just after the initiation of the event. However, the reactor pressure and temperature decrease from 30 sec in all the cases due to the occurrence of reactor scram at 30 sec for all the cases. The decreasing trend of these parameters continues until the end of the calculation. During the transient from 50 sec to 300 sec, the value of the reactor pressure and temperature is higher for the smaller break size of SGTR event, which can be attributed as the smaller coolant inventory loss.

The secondary side pressure of steam generator A is shown in Figure 4. In a similar trend to the primary pressure, the secondary side pressure of the steam generator is also increased to a peak value of 79.4 bar at 25 sec in all the cases. After the occurrence of reactor trip, the secondary side pressure starts to decrease and it follows an increasing and decreasing behavior as a result of the repeated opening and closing of safety relief valves of the steam generator during the calculation period as shown in Figure 4. It is mentioned that the secondary side pressure of steam generator B also shows similar behavior that of steam generator A.

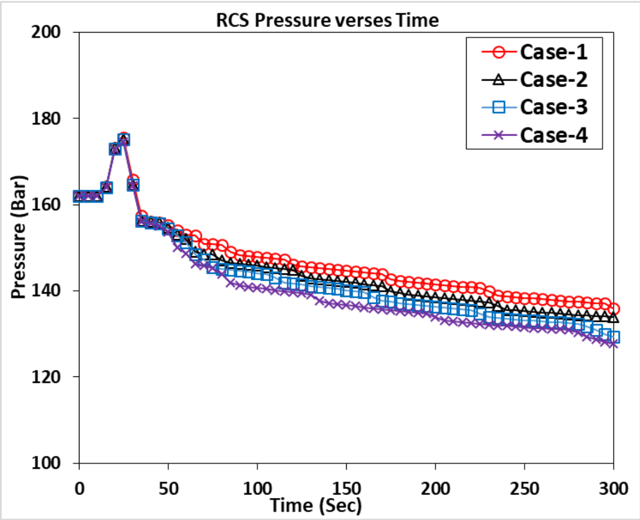

Figure 2. Pressure of RCS

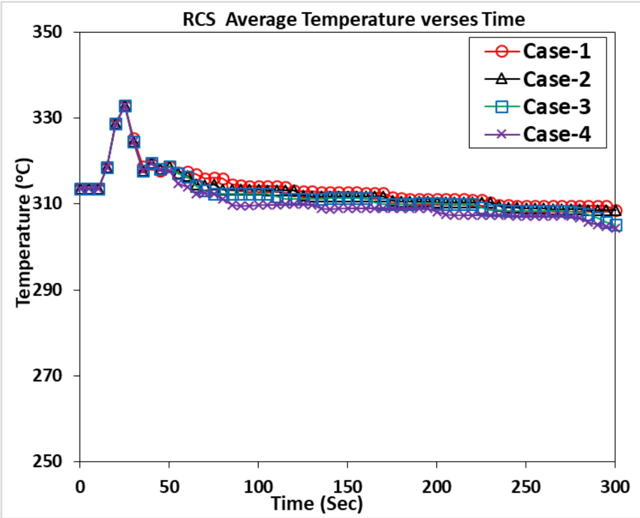

Figure 3. Average temperature of RCS

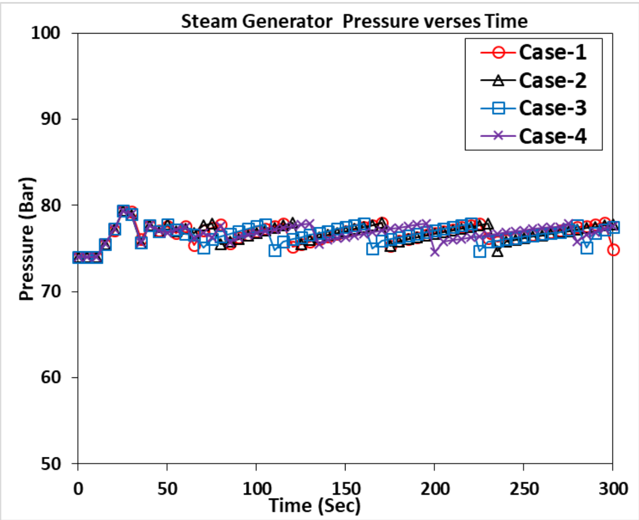

Figure 4. Secondary side pressure of steam generator A

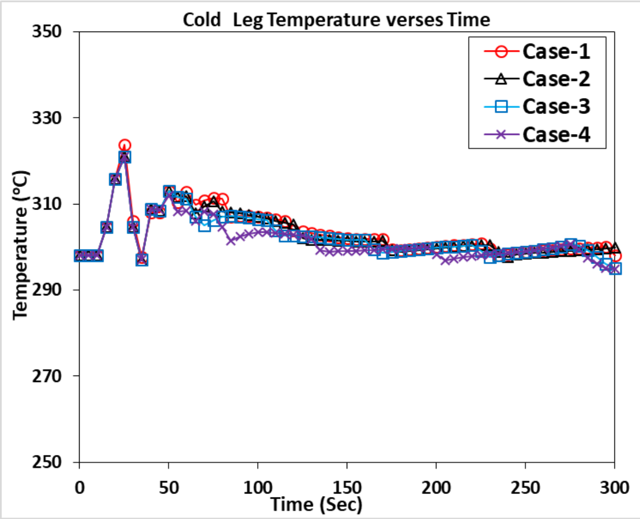

Figure 5. Temperature of cold leg B

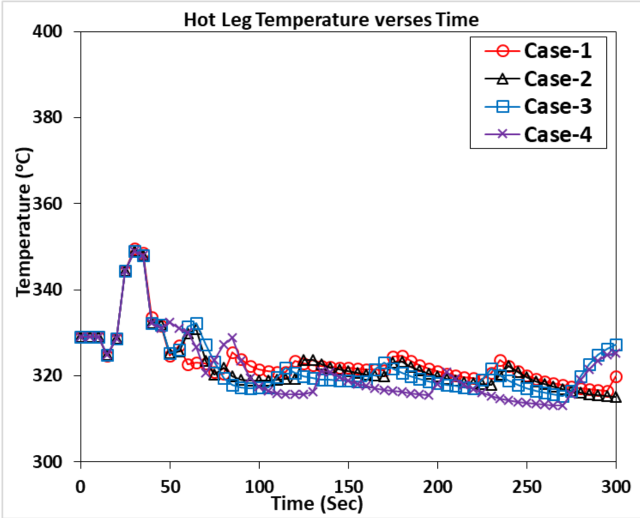

Figure 6. Temperature of hot leg A

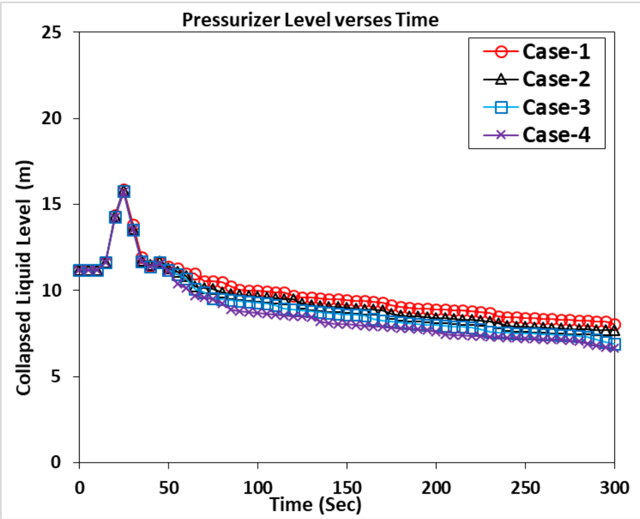

Figure 7. Collapsed liquid level of the pressurizer

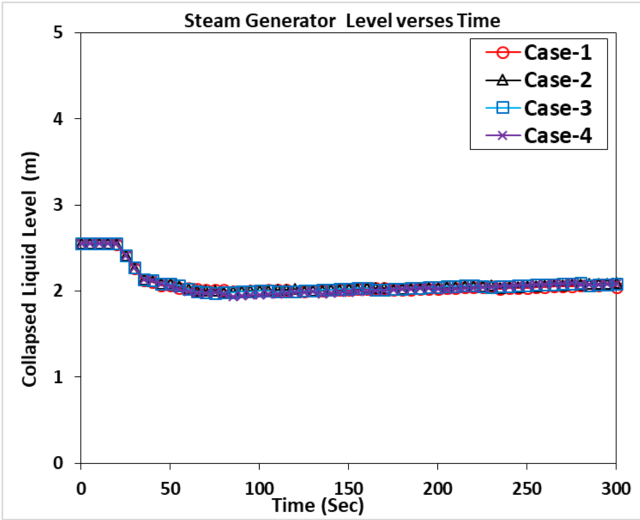

Figure 8. Collapsed liquid level of the steam generator A

The temperatures of cold leg B and hot leg A are shown in Figure 5 and Figure 6, respectively. As shown in Figure 5, the temperature of cold leg B increases to a peak value of 323.84 °C, 321.03 °C, 321.0 °C and 320.96 °C at 25 sec for Case 1, Case 2, Case 3, and Case 4 respectively from the initial temperature of 298.03 °C. As shown in Figure 6, the temperature of hot leg A starts to decrease just after the initiation of the SGTR event, which can be the result of the effect of the loss of steam generator inventory to the hot leg. However, the temperature of the hot leg increases to a peak value of around 349 °C for all the cases at 30 sec from the initial temperature of 329.08 °C, which agrees with the behavior of reactor pressure. After reaching to the peak value, the temperature of the cold leg and the hot leg follow the increasing and decreasing trend, in turn, due to the repeated opening and closing of safety relief valves of the steam generators during calculation period.

The collapsed liquid level of the pressurizer is shown in Figure 7. The liquid level of the pressurizer increases after the initiation of SGTR event from its initial level of 11.20 m due to the liquid surge towards the pressurizer. The liquid level of pressurizer increases to a peak value of 15.9 m, 15.8 m, 15.8 m, and 15.7 m at 20 sec for Case 1, Case 2, Case 3, and Case 4 respectively. After reaching the peak value, the pressurizer liquid level starts to drop rapidly due to the opening of the safety relief valve 1 of the pressurizer at 20 sec for all the cases. From 50 sec to the end of the calculation period, the liquid level of the pressurizer shows a plateau and it reaches a value of 8.0 m, 7.7 m, 6.9 m, and 6.6 m for Case 1, Case 2, Case 3, and Case 4 respectively, at 300 sec. In the plateau region, the value of the liquid level of the pressurizer is higher for the smaller break size of the SGTR due to the smaller coolant inventory loss for the smaller break size of the SGTR event.

The collapsed liquid level of the steam generator A is shown in Figure 8. The liquid level of the steam generator A decreases from the beginning of the SGTR event from its initial liquid level of 2.5 m due to the loss of the coolant inventory. The liquid level of steam generator also reaches a plateau phase from 50 sec to the end of the calculation and it reaches a value of 2.1 m for all the cases at 300 sec. It is mentioned that the liquid level of the steam generator B also follows a similar trend that of the steam generator A.

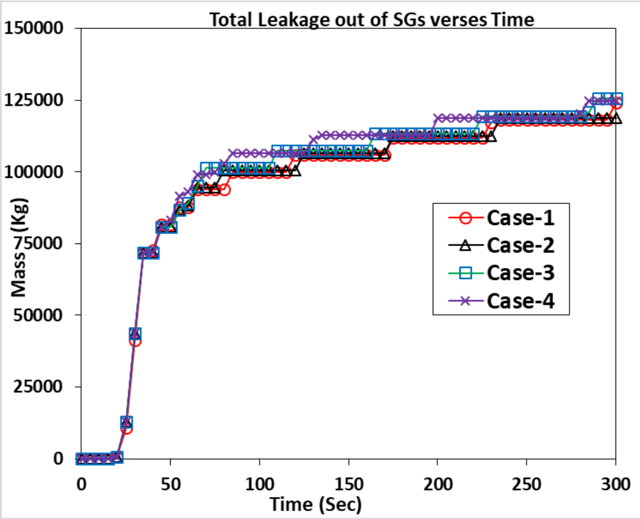

Figure 9. Total leakage out of steam generators

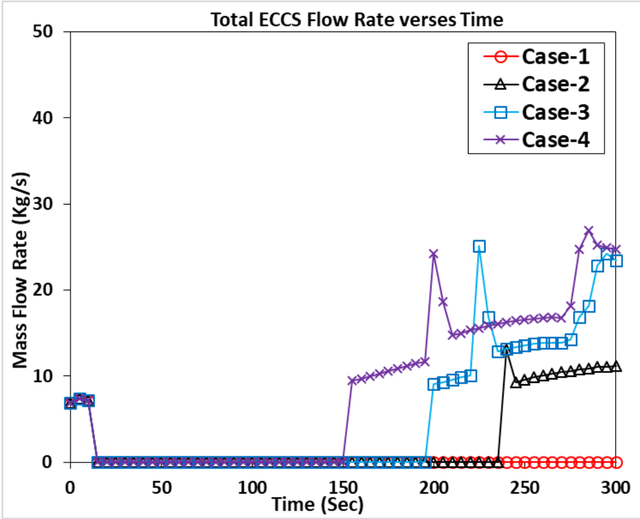

Figure 10. Total ECCS flow rate

The total leakage out of both steam generators is shown in Figure 9. The total leakage from steam generators rapidly increased to a value of around 100000 kg at 80 sec for each of the cases. The mass of total leakage increases slowly and it stands for a few seconds with almost a constant value due to the repeated opening and closing of safety relief valves of the steam generators during the calculation period. The mass of total leakage from steam generators reaches a value of 124093 kg, 118688 kg, 125523 kg, and 124783 kg for Case 1, Case 2, Case 3, and Case 4 respectively at 300 sec.

The ECCS injection flow rate to the reactor is shown in Figure 10. It is mentioning that the ECCS injection flow is very significant because it delivers makeup water to cool the reactor if normal coolant is lost from RCS. The default value of the ECCS injection flow rate is 6.94 kg/sec during the normal operation of the demo version of the PCTRAN model of VVER-1200 NPP, and this value becomes almost zero after the initiation of the SGTR event, as shown in Figure 10. There was no ECCS injection flow rate to the reactor in Case 1 due to the smaller coolant loss with comparison to other cases. On the other hand, the ECCS injection flow rate starts at 240 sec, 200 sec, and 155 sec for Case 2, Case 3, and Case 4 respectively. It implies that the larger SGTR event requires earlier coolant injection to the reactor using ECCS. The ECCS flow rate reaches a value of 11.2 kg/sec, 23.5 kg/sec, and 24.7 kg/sec for Case 2, Case 3, and Case 4 respectively, at the end of the calculation.

The reactor thermal power, the peak cladding temperature, and the peak fuel temperature are shown in Figures 11, 12, and 13 respectively. As shown in Figure 11, the thermal power starts to decrease after the initiation of the SGTR event from its operating power of 3200 MWth. At the time of the reactor scram at 30 sec, the reactor thermal power was 2470.84 MWth, 2344.37 MWth, 2335.0 MWth, and 2335.43 MWth for Case 1, Case 2, Case 3, and Case 4 respectively. The thermal power shows a rapid drop following the scram for all the cases. After 50 sec, the thermal power is stabilized and it reaches a value less than 100 MWth for all the cases at the end of the calculation.

As shown in Figure 12, the peak cladding temperature (PCT) value starts to decrease just after the initiation of the SGTR event from its initial value of 610.84 °C. The PCT drops rapidly to less than a value of 500 °C after the occurrence of reactor scram. After 50 sec, the PCT value is stabilized and it reaches a value of 316.7 °C, 316.5 °C, 313.5 °C, 312.5 °C for Case 1, Case 2, Case 3, and Case 4 respectively, at 300 sec. The PCT does not increase during the transient period from the reactor's normal operating condition. As shown in Figure 13, the peak fuel temperature value starts to decrease rapidly after the initiation of the SGTR event from its initial value of 1800 °C. At 35 sec, the peak fuel temperature reaches a value of 955.80 °C, 924.42 °C, 922.18 °C, 922.29 °C for Case 1, Case 2, Case 3, and Case 4 respectively. After 50 sec, the peak fuel temperature shows a plateau region during the calculation period and it reaches a value of 349.25 °C, 348.5 °C, 346.22 °C, 345.03 °C for Case 1, Case 2, Case 3, and Case 4 respectively, at 300 sec. The fuel temperature does not increase during the transient period from the reactor's normal operating condition.

It is mentioning that the comprehensive analysis of the behavior of thermal-hydraulic parameters during the SGTR event for different break sizes requires longer than 300 seconds in a pressurized water reactor. However, the plant responses and the behavior of thermal-hydraulic parameters do not show any risk to the safety viewpoints of VVER-1200 NPP during the PCTRAN simulation period of SGTR event in this study. Moreover, validation was not made by comparing the PCTRAN simulation results with any experimental results. The acceptance criteria for a transient of a pressurized water reactor are the low probability of a boiling crisis in the core, the maintaining pressure in the RCS below 110% of the design pressure, and no fuel melting occurrence in the core [21]. These acceptance criteria were maintained in this study during the 300 seconds simulation time, which means that the results obtained in this study are reasonable.

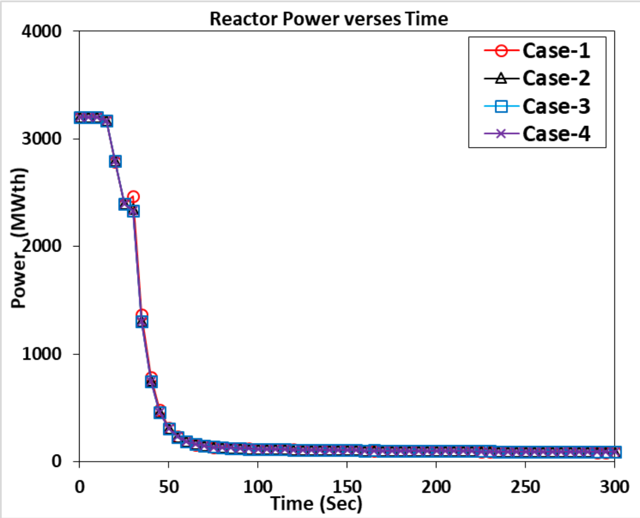

Figure 11. Reactor thermal power

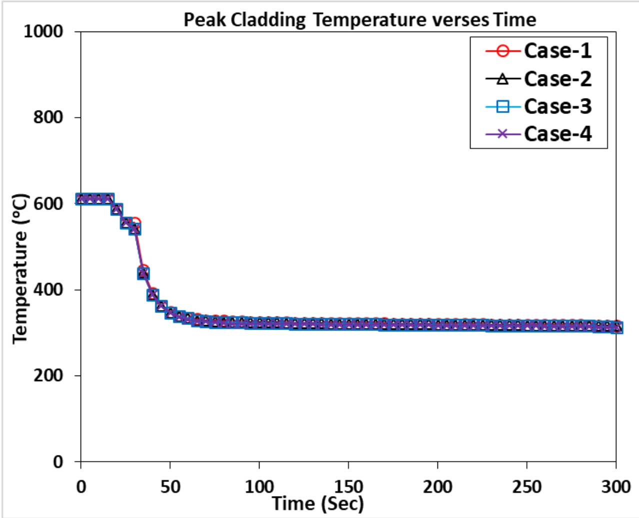

Figure 12. Peak cladding temperature

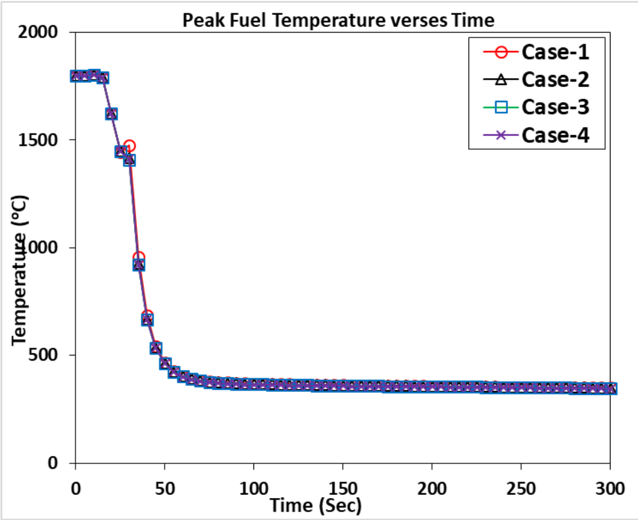

Figure 13. Peak fuel temperature

5. CONCLUSION

The analysis of thermal-hydraulics parameters during the SGTR event of the VVER-1200 pressurized water reactor is performed by applying the personal computer transient analyzer (PCTRAN) simulator. There are four cases namely, 25%, 50%, 75% and 100% (Case 4) of one tube rupture in two steam generators with the concurrent loss of AC power have been simulated in this study. There is no significant variation of time for the occurrence of the reactor coolant pump trip, the main feedwater pump trip, the turbine trip, the opening of pressurizer safety relief valve, the opening of steam generator safety relief valve, the starting of diesel generator A, and the starting of turbine driven auxiliary feedwater pump among four cases of SGTR events. The reactor scram occurred at 30 sec for Case 1, while the reactor scram occurred at 29.5 sec for all other cases.

The RCS pressure and the temperature, the hot leg temperature, and the cold leg temperature increase rapidly to a peak value due to the simultaneous loss of AC power with the SGTR event and it is followed by the rapid drop after the reactor scram and it reached to a stabilized value for all of the cases. The pressure and temperature of the RCS are higher for the smaller break size of the SGTR event due to the smaller coolant inventory loss. The secondary pressure of the steam generator is also increased to a peak value and it follows a repetitive increasing and decreasing trend due to the repeated opening and closing of safety relief valves of the steam generator during the calculation period. The liquid level of the pressurizer increases after the initiation of the SGTR event due to the liquid surge towards the pressurizer and it drops rapidly due to the opening of the safety relief valve of the pressurizer for all the cases. The liquid level of the pressurizer is higher for the smaller break size of the SGTR because of the smaller coolant inventory loss. The collapsed liquid level of the steam generator decreases from the beginning of the SGTR event due to the loss of the coolant inventory and it reaches a stabilized value. The mass of total leakage from the steam generator shows a rapid increase until the occurrence of the reactor trip and it becomes stabilized. The larger break size of the SGTR requires earlier coolant injection to the reactor using ECCS. The reactor thermal power, the peak cladding temperature, and the peak fuel temperature show a rapid drop after the initiation of the SGTR event, and these values are stabilized after the occurrence of the scram. There is no increase in the PCT and the peak fuel temperature during the calculation period.

The results of this study provide a valuable understanding of SGTR events with the concurrent loss of AC power for the PCTRAN model of VVER-1200 NPP. The demo version of the PCTRAN model of VVER-1200 NPP providing the accident scenario for 300 seconds only, is used, which is a limitation in this study. Further research is required to analyze the SGTR event of the VVER-1200 NPP by applying system codes.

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