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Evaluation of the Safety Margins during Shutdown for NPP Krško

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ABSTRACT

In the paper the results of RELAP5/mod3.3 calculations of critical parameters during shutdown for NPP Krško are presented. Conservative evaluations have been performed at NPP Krško to determine the minimum configuration of systems required for the safe shutdown operation. Critical parameters in these evaluations are defined as the time to start of the boiling and the time of the core dry-out. In order to have better insight into the available margins, the best estimate code RELAP5/mod3.3 has been used to calculate the same parameters. The analyzed transient is the loss of the Residual Heat Removal (RHR) system, which is used to remove decay heat during shutdown conditions. Several configurations that include open and closed Reactor Coolant System (RCS) were considered in the evaluation. The RELAP5/mod3.3 analysis of the loss of the RHR system has been performed for the following cases: 1) RCS closed and water solid, 2) RCS closed and partially drained, 3) Pressurizer manway open, Steam Generator (SG) U tubes partially drained, 4) Pressurizer and SG manways open, SG U tubes completely drained, 5) Pressurizer manway open, SGs drained, SG nozzle dams installed and 6) SG nozzle dams installed, pressurizer manway open, 1 inch break at RHR pump discharge in the loop with pressurizer. Both RHR trains were assumed in operation prior to start of the transient. The maximum average steady state temperature for all analyzed cases was limited to 333 K.

1 INTRODUCTION

In the past decade, operational experience and performance of the probabilistic safety analyses for the shutdown modes have indicated the importance of the risk contribution from those, previously considered safe operating modes. Most part of the risk comes from the unavailability of equipment due to maintenance activities undertaken during an outage. Adequate planning and preparation of activities during outages reduce both the probability and the consequences of possible events. Safety studies performed to-date on NPPs clearly indicated that the reduced inventory situations are the most critical periods. Special attention should be paid to loss of RCS inventory and residual heat removal events during mid-loop operation of PWR type reactors. The RCS inventory is essential to maintaining the overall decay heat removal function. The mid-loop operation represents a higher risk condition due to reduced RCS inventory. On the other hand, during shutdown operations the risk for the loss of RHR system rises because of many "single" failure potentials due to various maintenance configurations. The consequences of the loss of RHR system depend on a variety of factors, such as the configuration of the RCS (geometry of reactor, number of loops, position and status of the openings in the system), the mass of liquid in the system and the time after shutdown at which the transient occurred. Loss of RHR system causes the loss of forced flow through the core and coolant heat-up followed by the boiling in the RCS. If the RCS boundary is open the boiling will occur at atmospheric pressure. If the RCS boundary is closed boiling will occur at the RHR relief valve setpoint. The short time to start to boiling is associated with high decay power level and low RCS pressure. The presence of the openings in the system has two major consequences on transient outcome. First, due to low pressure (atmospheric conditions), a quick boiling in the core will occur. Secondly, the RCS inventory may be lost through the openings by either dislocating and spilling the liquid or by direct boil-off steam from the core.

The RELAP5/mod3.3 has been used to calculate "time to boiling" and "time to core uncovery" following loss of the residual heat removal capability for the plant shutdown states 1 to 5 (as defined in [1]). Following cases have been analyzed:
Case 1: RCS closed and water solid
Case 2: RCS closed and partially drained, the rest filled with noncondensables
Case 3: SG U tubes partially drained, pressurizer manway open
Case 4: SG U tubes completely drained, pressurizer and SG manways open
Case 5: SGs drained, SG nozzle dams installed, pressurizer manway open
Case 6: SG nozzle dams installed, pressurizer manway open, loss of RHR system, 1 inch break in the RHR train B (loop with pressurizer) at RHR pump discharge. Two different transient scenarios for this case have been analyzed: a) trip of both RHR pumps and b) closure of the RHR isolation valves at the accumulator discharge line.

The physical phenomena following the loss of the RHR system (e.g., liquid expansion and liquid entrainment, liquid disposal and discharge of the RCS inventory through the openings, noncondensable behaviour) have been studied. The differences between the analyzed cases due to different configurations as well as initial liquid and noncondensable content have been discussed.

2 CALCULATIONAL MODEL FOR NPP KRŠKO

For the analysis of the loss of the RHR system the RELAP5/mod3.3 model for NPP Krško developed at FER Zagreb has been used. The model is based on the RELAP5/mod3.3 model that has been developed in compliance with [3], described in [4] and qualified on the steady state level, [5]. Previously, the RELAP5/MOD2 model for NPP Krško that includes a detailed model of the RHR system has been developed and used for the analysis of the transients in the shutdown conditions, [6]. Also, it has been validated for the loss of RHR analysis, [7]. For the purpose of the evaluation of the safety margins during shutdown for NPP Krško, the model of the RHR system from [6] has been upgraded and included in the base NPP Krško model described in [4]. Parts of the Nuclear Steam Supply System (NSSS) important for power operation that are not used at shutdown have been excluded from the model. The following are the differences of the NPP Krško model used in the analysis when compared with the base model: 1) Models that are omitted in the model include: Safety Injection system, Feedwater system and Auxiliary Feedwater system. and 2) Control systems that are not used during shutdown were omitted in the model (e.g., pressurizer pressure and level control system, Rod control system, SG level control system, etc.). The RELAP5/mod3.3 model (including RHR system) used in this analysis consists of 765 volumes and 793 junctions. The model has 273 heat structures with total number of mesh points equal to 1785. Both RHR trains were modeled. The RHR inlet and outlet are connected with the RCS hot and cold legs by downward oriented valve junctions (from the hot legs) and with the valves to the Emergency Core Cooling System (ECCS) accumulator injection point (to the cold legs), respectively. The main components of the RHR system are the RHR pump, RHR heat exchanger and the accompanying isolation valves. Each train to the inlet of the

RHR system is equipped with a pressure relief valve (RHR valve 1 - upflow of the RHR pump) aimed to protect the system from inadvertent overpressurization during plant cooldown and startup. On the RHR discharge side each RHR train is equipped with a pressure relief valve (RHR valve 2 - downflow of the RHR pump) aimed to relieve the back-leakage flow through the valves separating the RHR system from the RCS. The SG secondary sides were assumed to be dried out and filled with air at atmospheric pressure. No credit has been taken for heat transfer from the primary to secondary side as well as for heat losses from primary side to the environment.

2.1 Steady State Calculation

In order to achieve steady state for the cases 1 through 6 the controlled draining of the RCS in accordance with the procedure described in [2] has been performed. The boundary and initial conditions for the analyzed cases are summarized in Table 1. A conservatively high decay power value that corresponds to one day after shutdown was assumed constant throughout the transient simulation. The sequential procedure to achieve the steady state for the analyzed cases is described below.

Case 1 - Prior to the start of the controlled draining the RCS conditions correspond to plant shutdown state 1 with RCS water solid and both trains of RHR in operation. Hot leg pressure equals to 5.93E5 Pa.

Case 2 - The RCS is drained starting from the Case 1 using letdown flow until the level equal to 1.7 m above the center leg elevation is attained. Simultaneously, the air at pressure 4.71E5 Pa is admitted to the pressurizer and reactor vessel head through pressurizer relief valve and reactor vessel head vent system, respectively. The SG U tubes are filled with liquid.

Case 3 - The RCS is depressurized from the Case 1 to atmospheric conditions. The RCS level equal to 1.7 m above center leg elevation is maintained. The SG U-tubes are partially drained due to saturation conditions at the top. After steady state conditions had been attained, the pressurizer manway is opened.

Case 4 - Starting from the Case 3 the letdown flow is used to completely drain the SGs. The RCS level is controled at level: center leg (C.L.) elevation + 0.7 m. Finally, the inlet and outlet manways at both SGs are opened.

Case 5, Case 6 - Starting from the Case 4, the SGs are isolated from the rest of the RCS.

The Case 6 was analyzed with two scenarios of the loss of the RHR system: a) **case a**: trip of both RHR pumps and b) **case b**: closure of the RHR isolation valves just before discharge line. In the analysis for the **case b** it was assumed that the trip of RHR pump is initiated when the void fraction in the volume before the pump increases above 0.3.

Table 1: Initial and boundary conditions for the analysis of the loss of the RHR system

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Hot leg pressure (Pa)	5.93E5	4.91E5	1.177E5	1.081E5	1.081E5	1.081E5
Average temperature (K)	333.15	333.18	333.17	333.19	333.19	333.19
Core inlet m. flow (kg/s)	269.8	269.8	271.1	269.2	269.2	269.2
Core power (MW)	12.41	12.41	12.41	12.41	12.41	12.41
Initial RCS mass (kg)	190188.	153604.	136836.	73409.	73409.	73409.
RCS level above center leg elevation (m)	RCS solid	1.7	1.7	0.7	0.7	0.7
Manways open	-	-	pressurizer	pressurizer SGs	pressurizer	pressurizer

3 CALCULATION RESULTS

Results of the loss of the RHR system for NPP Krško are graphically presented in Figure 1 to Figure 9. The results for the critical parameters during shutdown for NPP Krško are summarized in Table 2. The results are separately discussed for the cases with closed RCS (Case 1 and Case 2) and for the cases with open RCS (Cases 3, 4, 5 and 6), respectively.

RCS closed: Case 1 and Case 2

Following the loss of the RHR capability, the forced flow through the core had ceased and the coolant heated up, Figure 1.

Case 1: For the water solid case (Case 1), a rapid pressure rise occurred and the RHR relief valve 1 in both RHR trains opened at the very beginning of the transient, Figure 2. The pressure in the system was maintained between the opening and closing setpoint pressure of the RHR relief valve 1. The boiling in the core has started at time = 12060 sec, followed by a pressure rise and an increased flow through the relief valves. Reactor Pressure Vessel (RPV) mass was being reduced accordingly, Figure 7.

Case 2: In the Case 2 much slower pressure increase than in the Case 1 was obtained, Figure 1. Fluid expansion was accommodated by a large quantity of air present in the system. Before the begin of the boiling the liquid expanded in the upper head, thus compressing the air blanket. As soon as boiling in the core started the vapor flowed upwards into the upper head and mixed with the air. Following the start of the boiling (at time = 7053 sec) the more rapid pressure rise resulted. At time = 12340 sec the discharge through the RHR relief valve 1 started. The air was expelled from the reactor pressure vessel, while it remained in the pressurizer till the end of simulation. RPV mass was being slowly reduced after begin of boiling, Figure 7. The rapid decrease of the RPV mass resulted first after begin of the discharge through the opening, Figure 2, Figure 7.

Core dry-out, Figure 9, occurred for the Case 1 at time = 15300 sec, and for Case 2 at time = 14820 sec, respectively. For both cases the core dry-out started when reactor pressure vessel inventory depleted to approximately 25 tons, Figure 7.

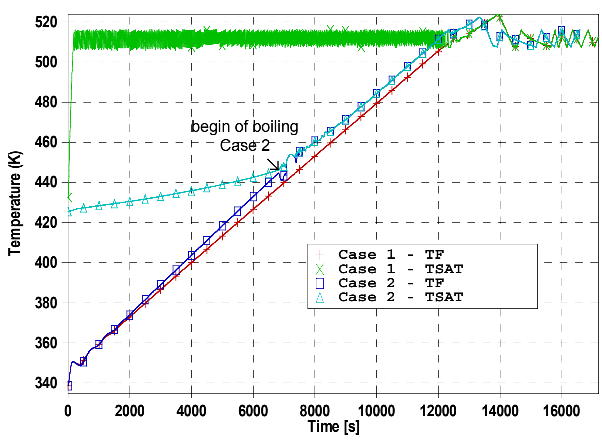

Figure 1: Fluid temperature (TF) at the top of the core and saturation temperature (TSAT)

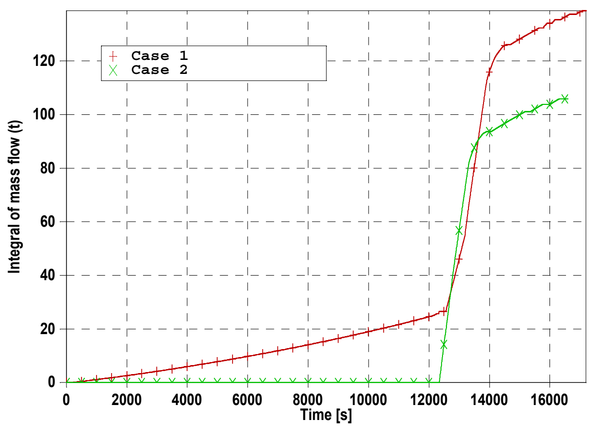

Figure 2: Discharged mass through the RHR relief valves

RCS open: Case 3, Case 4, Case 5, Case 6

Following the loss of the RHR capability the coolant heated-up and the boiling occurred very fast after start of the transient, Table 2, because of low system pressure.

Case 3: Following the start of boiling, liquid entrainment into pressurizer surge line and pressurizer took place. The vapor at the top of the SG U tubes condensed and the SG U-tubes were entirely filled with liquid. Discharge through the pressurizer manway began first after the primary pressure reached 2.1E5 Pa, Figure 3 and Figure 4, because of high initial RCS liquid mass and the great amount of entrained liquid into pressurizer and the pressurizer surge line. In particular, for NPP Krško, the connection junction of the pressurizer surge line with the hot leg (centrally and side oriented) and the orientation of the first part of the surge line (almost horizontal) contribute to clogging of the surge line with the liquid and hamper the discharge of the vapor through the pressurizer manway, [9] and [10]. Along with the emptying of the hot legs, liquid entrainment into the pressurizer surge line was stopped. Consequently, the RCS pressure decreased (at app. 4000 sec) and the flow through the pressurizer manway remained pure vapor, Figure 3, Figure 4. Core dry-out occurred at time = 5800 sec when reactor pressure vessel mass dropped to approximately 21 tons, Figure 8, Figure 9.

Case 4: Because of the fact that prior to the begin of the transient the liquid level was close to the SG manway openings, the increase of the liquid specific volume led to the discharge of the liquid through the SG manways even before the boiling started, Table 2 and Figure 4. Unlike the pressurizer surge line which is prone to the clogging because of liquid entrainment, the position and orientation of the SG inlet manways provided a free path for discharge to the environment. The RCS pressure, Figure 3, remained low throughout the simulation and the negligible amount of the RCS inventory was discharged through the pressurizer manway, Figure 4. The core dry-out began when reactor pressure vessel mass reached about 22.5 tons (at time= 3615 sec), Figure 8 and Figure 9.

Case 5: Following the start of the boiling a rapid expansion into pressurizer and pressurizer surge line resulted. As soon as enough pressure was built-up, a discharge through the pressurizer manway started, Figure 3 and Figure 4. When compared with the Case 3 much less pressure had to be built up to begin the discharge through the pressurizer manway. In the Case 5 the initial RCS mass was much less than in the Case 3 where the SG U tubes were filled with liquid before transient begin. Consequently, in the Case 5, the emptying of the hot legs and the decrease of the liquid entrainment into the pressurizer surge line occurred much earlier than in the Case 3. Thus, in the Case 5 the free path for the vapor relief through the pressurizer manway was obtained soon in the transient. The core dry-out occurred at time= 4000 sec, Figure 9, Table 2.

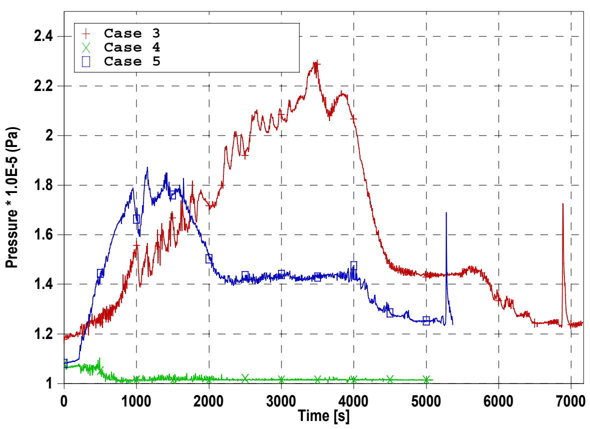

Figure 3: Hot leg (loop with pressurizer) pressure (Case 3, Case 4, Case 5)

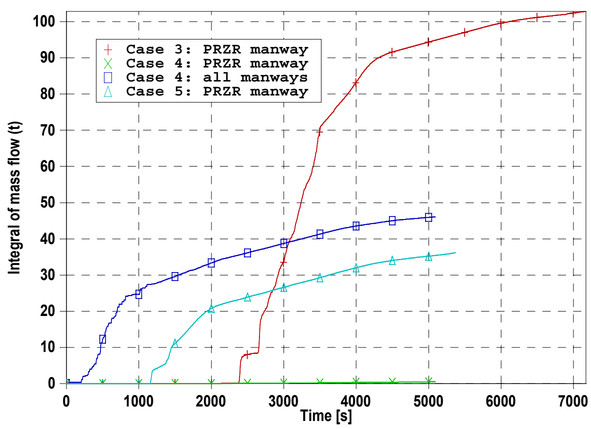

Figure 4: Discharged mass through the manways (Case 3, Case 4, Case 5)

Case 6: Following the break occurrence, RCS pressure initially dropped, Figure 5. Similarly to the Case 3 and Case 5, the discharge through the pressurizer manway started first after sufficient pressure has been built-up (at app. time = 1000 sec), Figure 5, Figure 6. In the **case b** a much greater loss through the break than for the **case a** was obtained because RHR pumps were running. Consequently, an earlier emptying of the hot legs as well as the earlier RCS pressure drop in the **case b** than in the **case a** was obtained, Figure 5. At time=1285 sec in the **case b** the RHR pump in the loop with the break was stopped on a signal: void fraction greater than 0.3. After that point, the break flow for the **case b** decreased. In the **case a**, the high RCS pressure was maintained for about 800 sec longer than for the **case b.** Therefore, the discharged mass through pressurizer manway during this phase was considerably higher than for the **case b,** Figure 6. After emptying the pressurizer as well as pressurizer surge line and the subsequent pressure drop at approximately 1700 sec, the flow through the pressurizer manway for the **case a** was equal to that of the **case b**, Figure 5, Figure 6. Finally, almost the same amounts of the discharged masses through the openings as well as the time of the core dry-out for both the **case a** and **case b** were obtained (3570 sec and 3575 sec, respectively), Figure 9, Table 2.

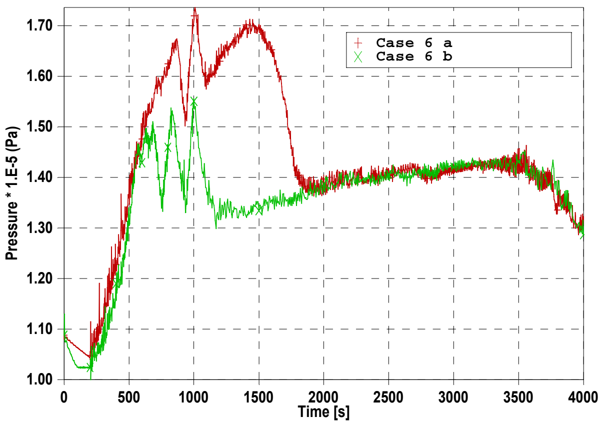

Figure 5**:** Hot leg (loop with pressurizer) pressure (Case 6 a, Case 6 b)

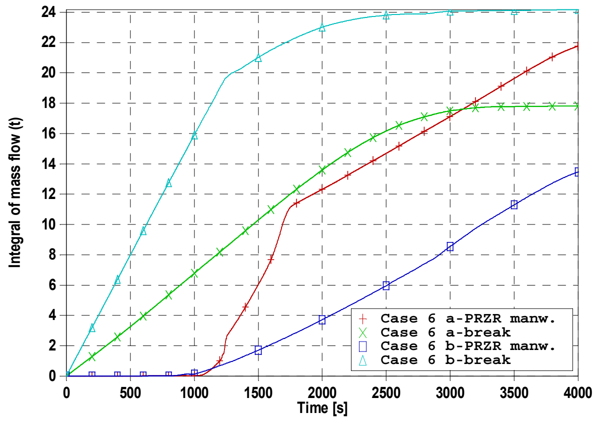

Figure 6**:** Discharged mass through pressurizer manway and break (Case 6 a, Case 6 b)

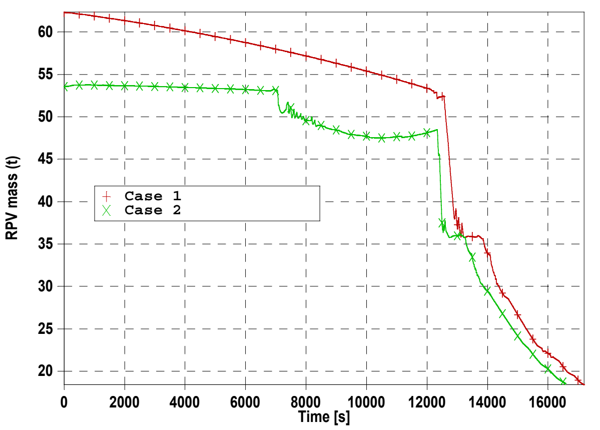

Figure 7**:** Reactor pressure vessel mass (Case 1, Case 2)

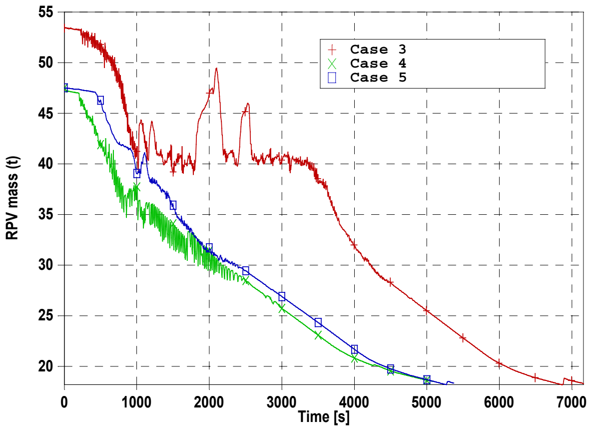

Figure 8**:** Reactor pressure vessel mass (Case 3, Case 4, Case 5)

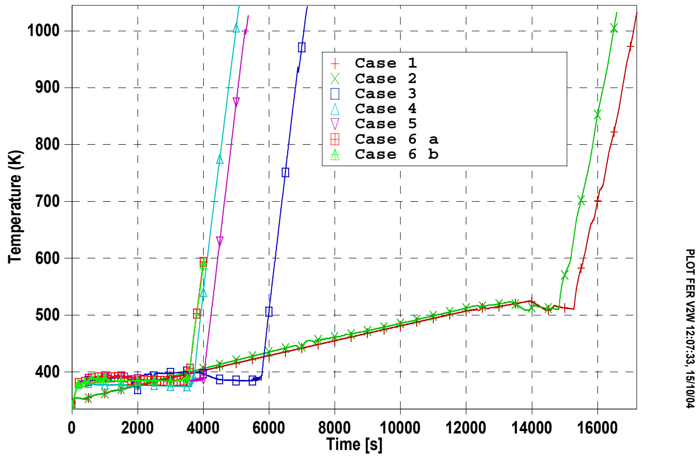

Figure 9**:** Fuel cladding temperature (N=11)

Table 2: Critical parameters for the loss of RHR system for NPP Krško

Parameter	**Case 1**	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
Time to boiling (sec)	12060	7053	249	211	499	a:272 b:291
Time to core dry-out (sec)	15300	14820	5800	3615	4000	a:3570 b:3575

4 CONCLUSION

The evaluation of the safety margins during shutdown for NPP Krško has been performed using RELAP5/mod3.3 code. Critical parameters (time to boiling and time to core dry-out) were determined by analyzing the loss of RHR system for several configurations that include open and closed RCS. Following conclusions can be drawn from the analysis of the loss of RHR system:

• A relatively small difference in the time of core dry-out between the two cases with the closed RCS (Case 1 and Case 2) was obtained (15300 sec versus 14820 sec) for the significant difference in the initial RCS mass (190.2 versus 153.6 tons). For the Case 1 (water solid) the continuous liquid discharge through the RHR relief valve has depleted the RCS from the very beginning of the transient, while in the Case 2, the air in the upper head and the pressurizer accommodated the pressure rise and thus prevented the release through the relief valves for almost 3.5 hours.

• The dominant phenomena for the cases with one opening (pressurizer manway, i.e., the cases 3 and 5) is the build-up of RCS pressure to commence the relief through the manway. Since for all the analyzed cases the hot legs were initially entirely filled with liquid, liquid entrainment into pressurizer surge line and pressurizer have prevailed in the first phase of the transient. Following the emptying of the hot legs, liquid entrainment into pressurizer surge line ceased and the RCS pressure decreased. In the second phase of the transient a free path for the vapor to the pressurizer manway was provided.

• In the Case 4 the dominant phenomena was the discharge through the two pairs of SG manways (inlet and outlet) whose position and configuration caused a quick depletion of the RCS inventory, while the discharge through the pressurizer manway was negligible. When compared with the Case 5 (the same amount of the initial RCS mass) an earlier begin of discharge and the faster depletion of the RCS mass was obtained. Also, in the Case 4 an earlier core dry-out than in the Case 5 resulted (3615 versus 4000 sec). This can be referred to the difference in configuration of the openings for discharge (pressurizer manway in the Case 5 and SG manways in the Case 4).

- The shortest times to core dry-out were obtained for the cases with the break (Case 6 a and Case 6 b). For both cases similar results for the time of the core dry-out were obtained. In the Case 6 b (RHR pumps running) the initial flow through the break was higher than for the Case 6 b. However, this resulted in the earlier emptying of the hot legs accompanied by a lower liquid entrainment into the pressurizer surge line and an earlier pressure drop. As already discussed, the amount of the discharge through the pressurizer manway depend on pressure when hot legs contain liquid. Thus, for the Case 6 b, a higher discharge through the break was compensated by a lower discharge through the pressurizer manway.
- The critical parameters for the analyzed configurations indicate a late start of boiling for the cases with closed system (2 to 3 hours) and an early start of boiling for the cases with open system (4 to 8 minutes). A delay of the time of the start of the boiling for the Case 5 when compared with the Case 3 can be referred to the differences in the RCS configuration (SG nozzle dams in the Case 5). In the Case 5, a fast increase of the pressure and saturation temperature at the top of the reactor core occurred due to the unavailability of the SGs to accommodate the liquid expansion. A shortest time to core dry-out was about one hour (Case 4, Case 6 a and Case 6 b, respectively) and the latest core dry-out was obtained for the liquid solid system (Case 1), 4.2 hours.

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