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Results of Exemplary LOCA Analyses with ATHLET for a Generic VVER-1000 Plant

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The present paper describes the analyses of the ATHLET simulations of two loss-of-coolant accident (LOCA) sequences, utilizing a generic VVER-1000 input deck:

1. Beyond design basis accident (BDBA): LOCA in the cold leg (close to the RPV nozzle), diameter 250 mm with failure of LPI and HPI systems.
2. Design basis accident (DBA): LOCA in the cold leg (close to the RPV nozzle), diameter 250 mm with operating LPI and HPI systems.

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1. Introduction

In the investigation of violations of the expected normal operation and design basis accident (DBA) should use relevant computer codes for thermohydraulics. In many cases the safety parameters such as the temperature of the fuel and cladding and peak linear heat capacity cannot be measured directly and their values cannot be represented by the reactor operator. Therefore it should be estimated of the reactor core states by special computer codes in order to set the values of the parameters in the operating procedures.

Owing to the absence complete empirical basis possible analysis of nonstationary normal and accident processes in the reactor facility is a calculation analysis which has a theoretical prediction character and is not the generalization of empirical data.

Thermohydrodynamic (thermohydraulic) codes are one of the groups of computer programs that are required for justification of a nuclear facility safety analysis and include subgroup "system thermohydraulic codes". Programs of this subgroup are usually divided into codes of the conservative and realistic estimates. The second type of code called best estimate codes. This type does not contain specific models of individual plant elements and processes occurring in them, based on empirical data. Therefore best estimate codes are sufficiently accurate and universal, they are applicable to the whole class research facilities.

System thermohydraulic codes are software systems, designed to simulate the parameters of the coolant throughout the nuclear power plant. In case of abnormal mode initiation and especially of emergency modes the coolant phase composition changes. As in the coolant can be realized various flow regimes and heat transfer for the correct description of such processes to be modeled vapor-liquid mixture in the approximation separate phase flow. System codes in which the coolant is described in the mentioned approximation, were scalled realistic or best estimate codes.

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One of the representatives of this type of codes is a software package ATHLET which is based on modern deterministic models.

The thermal-hydraulic computer code ATHLET (Analysis of the THermal-hydraulics of LEaks and Transients) is being developed by the Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) for the analysis of anticipated and abnormal plant transients, small and intermediate leaks as well as large breaks in light water reactors. ATHLET can be applied for all types of design base and beyond design base incidents and accidents without core damage in light water reactors, like PWR, BWR, VVER, and RBMK.

2. Beyond design basis accident (BDBA)

The first accident to be analyzed is a loss of coolant accident (LOCA) in the cold leg close to the RPV nozzle with a 250 mm diameter of the leakage. A failure of the high and low pressure injection (HPI and LPI) systems is assumed.
The sensitivity of the simulation results regarding variations in the input data is investigated. Therefore, we consider three different cases of the basic input file:

1. Pressurizer attached to the 4th loop, decay heat and pump coast down curve as described in [1].
2. Pressurizer attached to the 4th loop, decay heat according to Way-Wigner formula, pump coast down curve as described by an idealized exponential behavior (cf. [2]).
3. The same as 2nd case, but the pressurizer is in 1st loop.

In order to facilitate the comparison of the influence of the abovementioned variations in the input deck, the graphs for the three different cases are either plotted together in one common diagram or plotted in a row for the respective treated parameter.
Let consider residual water mass together with total mass for primary thermo-fluid dynamic (TF) systems (Figure 2.1). The red and the blue line in Figure 2.1 are hidden behind the purple line because the residual water masses of all cases are close to zero and the scaling of the y-axis is quite large.

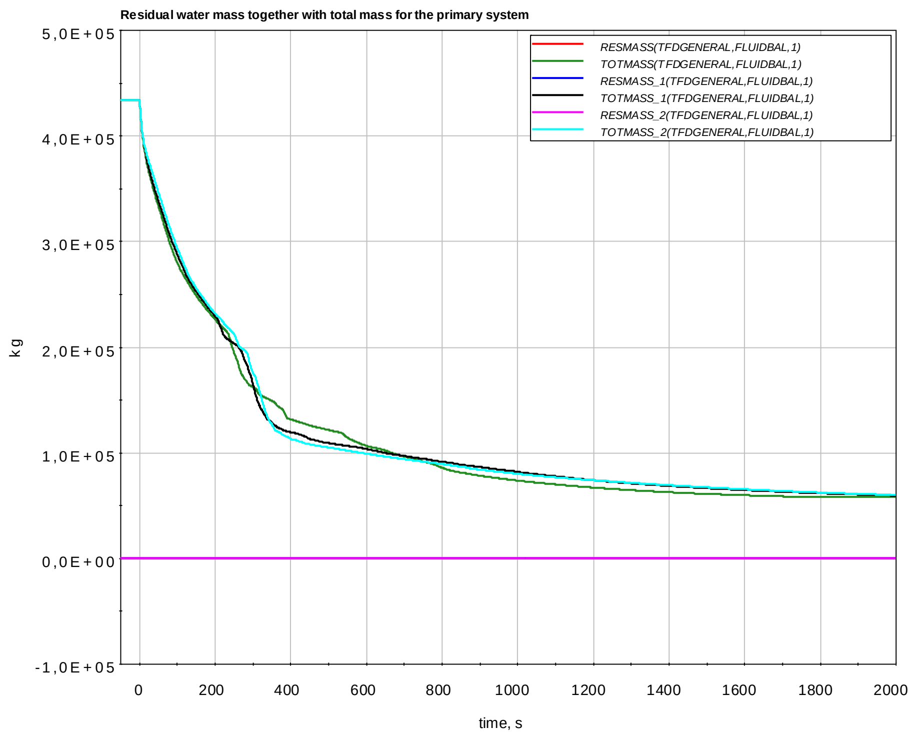

Figure 2.1 Residual water mass together with total mass for the primary system (red, green – 1st case, blue, black – 2nd case, purple, azure – 3rd case)

Obviously, the quality assurance plots of the 3rd case are similar to those of the 2nd case. But there still remain differences in the behavior of some physical variables. However, in the further we consider only the 1st and the 2nd case.

Let consider behavior of the BRU-A and BRU-K valves.

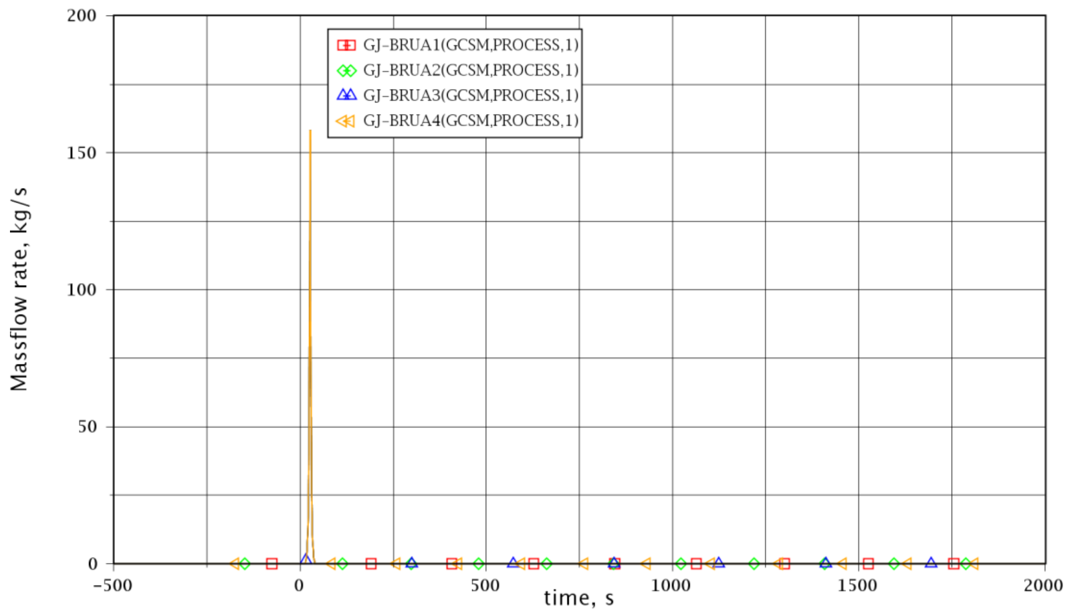

Figure 2.2 BRU-A mass flow rates (1st case)

Note that the yellow curve in Figure 2.2 hides the other curves; in the treated case, all BRU-A mass flows exhibit the same peak. Thus, the total BRU-A mass flow peak is somewhat higher than 600 kg/s. In the second case, all BRU-A mass flow rates are equal zero.

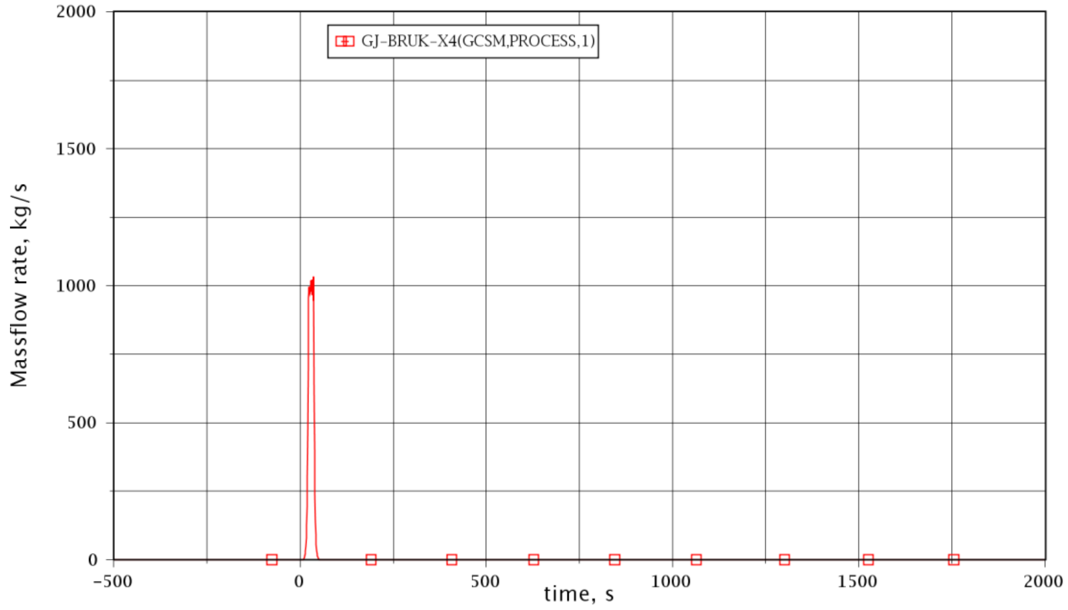

Figure 2.3 BRU-K mass flow rate (1st case)

Note that the BRU-K mass flow rates shown in Figure 2.3 and Figure 2.4 include the discharge through all four BRU-K valves. This means for both figures that the flow rate per BRU-K valve is about 250 kg/s, which is the maximum permitted flow rate.

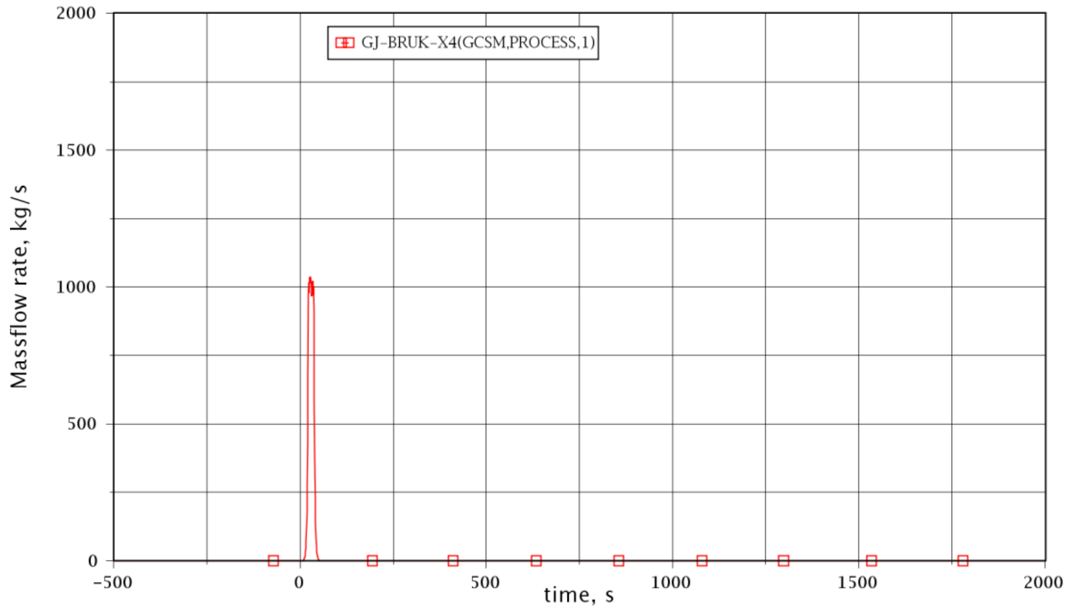

Figure 2.4 BRU-K mass flow rate (2nd case)

To analyze loss-of-coolant accident (LOCA) we consider only the second case where the pressurizer is attached to the 4^{th} loop, the decay heat is prescribed according to the Way-Wigner formula, and the pump coast down curve described by an idealized exponential behavior ([2]).
LOCA starts at time 0 s, when the leakage of DN 250 mm is opened (Figure 2.5). Simultaneously, the level of the coolant in the pressurizer begins to drop (Figure 2.6). Rapid reduction of pressure in the primary circuit of the reactor installation (Figure 2.7) begins and after about 0.5 s the pressure above the reactor core falls below 14.51 MPa, which is a condition for the actuation of the SCRAM signal.

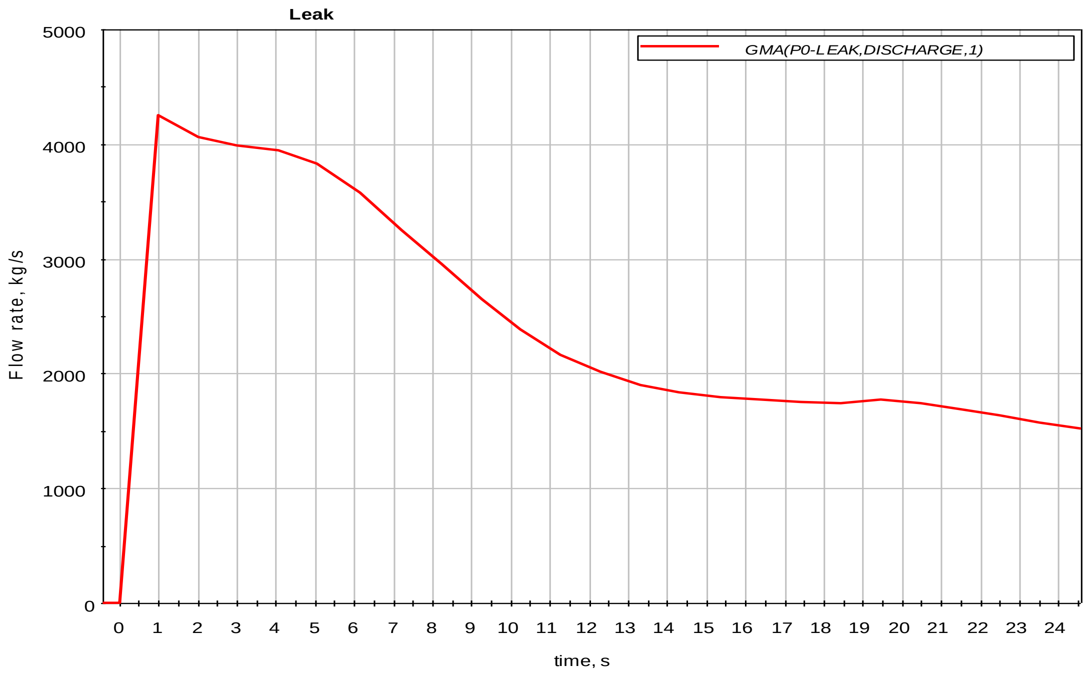

Figure 2.5 Leak opening

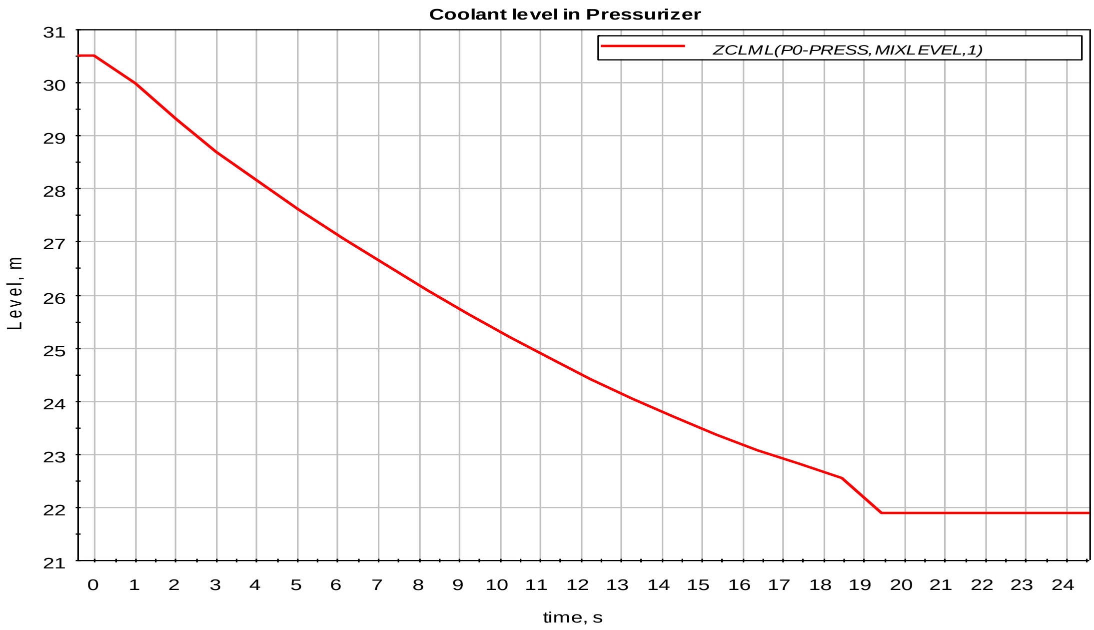

Figure 2.6 Coolant level in Pressurizer

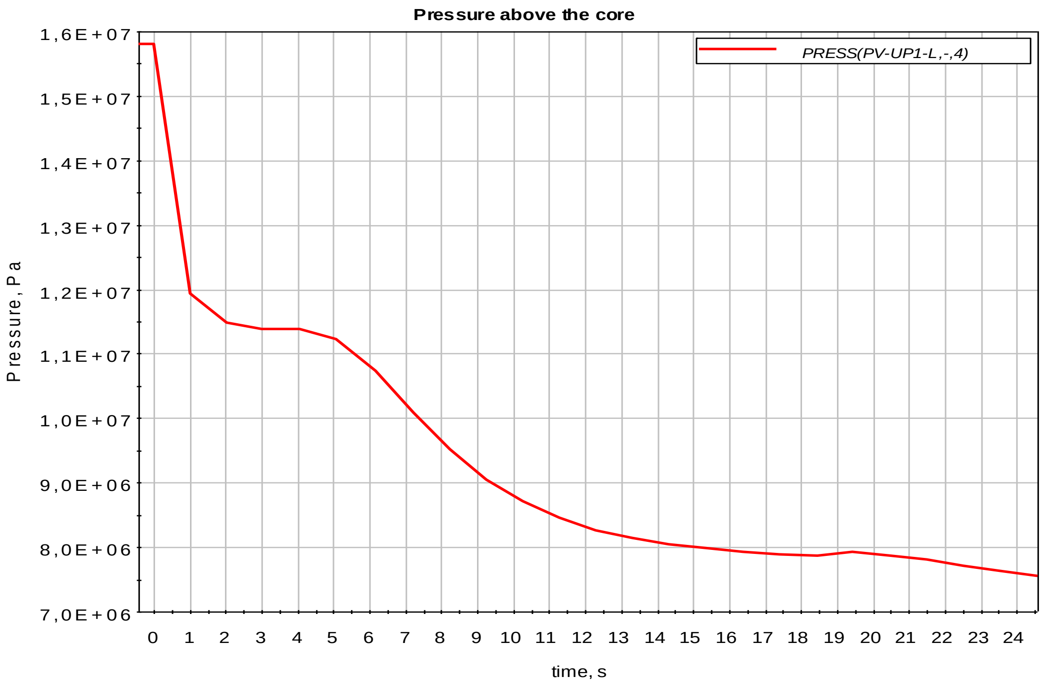

Figure 2.7 Pressure above the core

When the SCRAM is activated, the control rods are immediately inserted into the active zone (the time of fall of the rods is 1.5 to 4 s) and the main circulation pumps are disconnected (Figure 2.8, Figure 2.9). Further procedures which would be performed in a real VVER-1000 plant are not included in this simulation. The neutron power of the reactor starts to decrease rapidly. With a delay of 4 seconds, after the full introduction of the control rods into the active zone, the turbine trip signal is given and the turbine mass flow coasts down linearly within 10 s (Figure 2.10) – this behavior was specified in the ATHLET input deck.

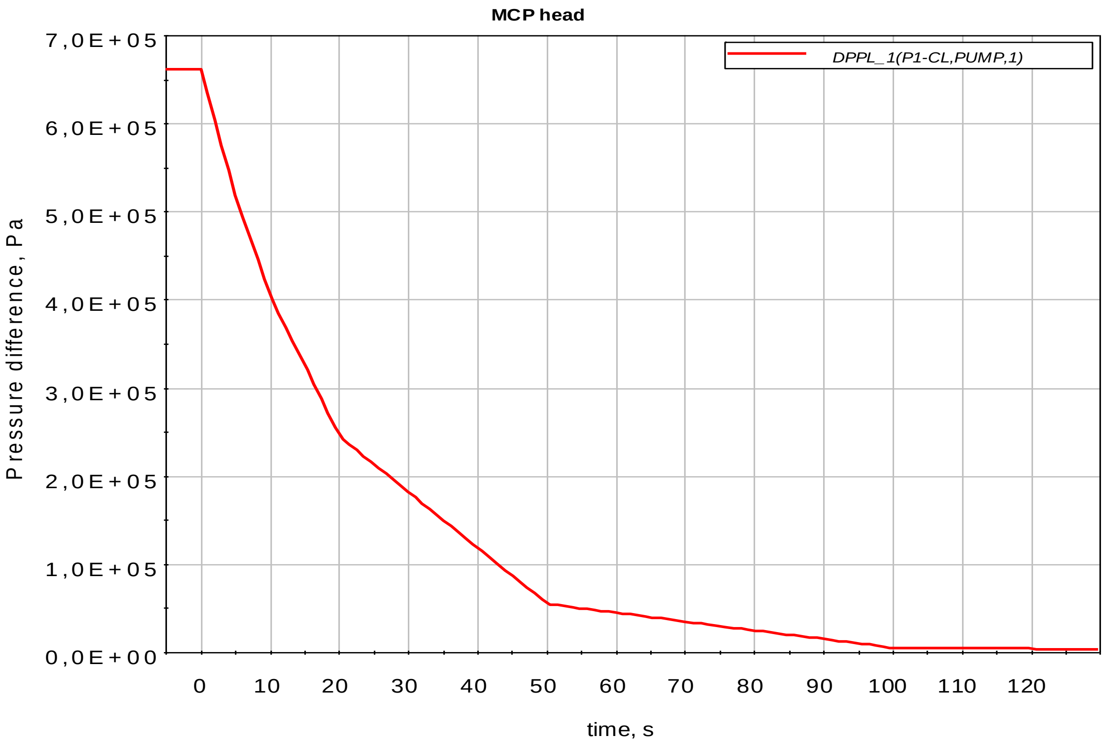

Figure 2.8 Main circulation pump head

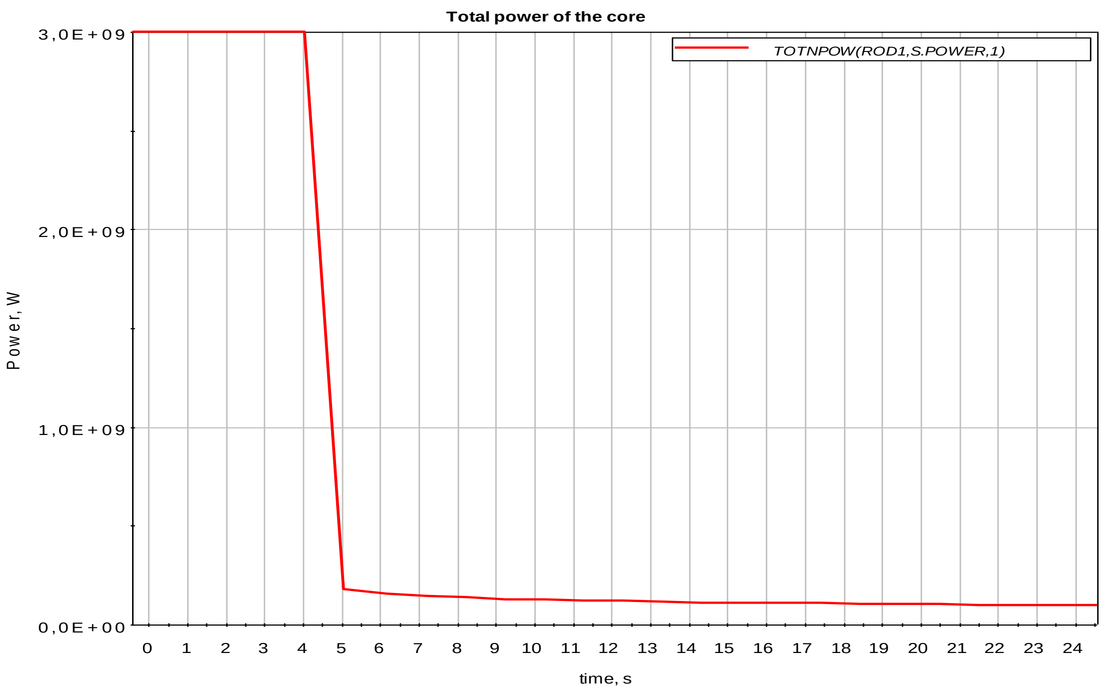

Figure 2.9 Total power of the core

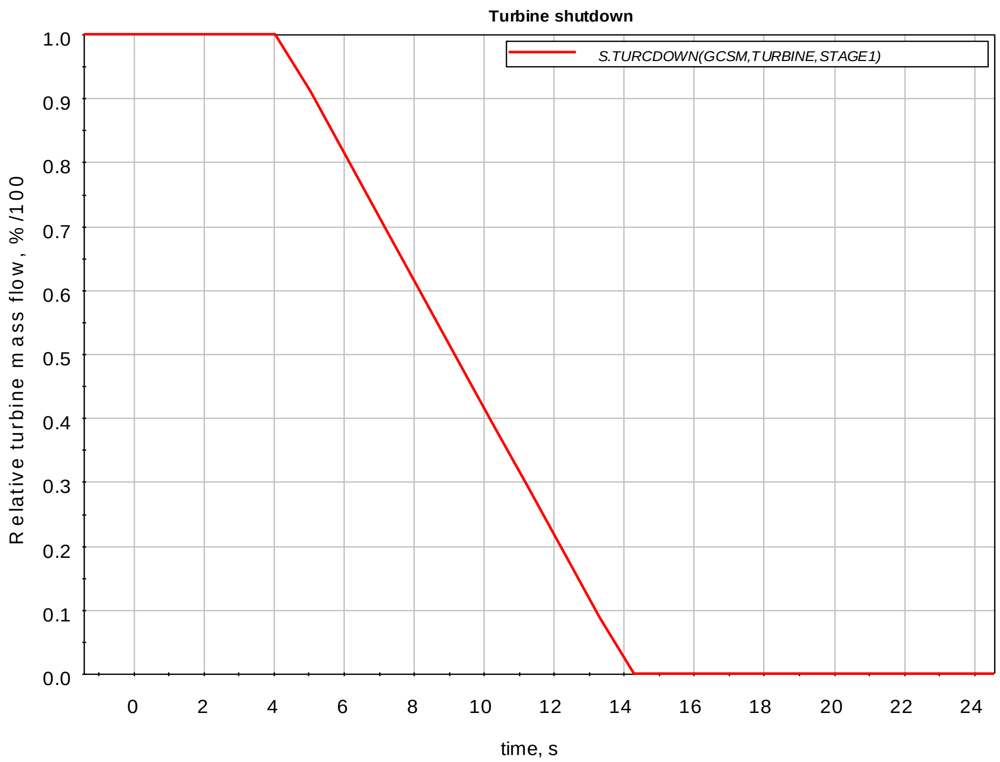

Figure 2.10 Turbine shutdown

As the main steam valve of the turbine closes, steam pressure in the steam generators begins to increase (Figure 2.11). Since the signal "fast turbine unloading" is active, the BRU-K valve opens when a pressure of 6.67 MPa is reached, dumping surpluses of the produced steam into the turbine condenser (Figure 2.12). The valve opens at 9 seconds and closes at 51 seconds when the pressure sinks below 5.59 MPa. As can be seen in Figure 2.12, the mass flow through the BRU-K valve is controlled around a maximum discharge rate of 250 kg/s per valve and remains sub-critical during the discharge period. Due to the fact that the pressure in the steam generators does not reach the value of 7.16 MPa (the maximum pressure in Figure 2.11 is 7.149 MPa), the BRU-A valve does not open.

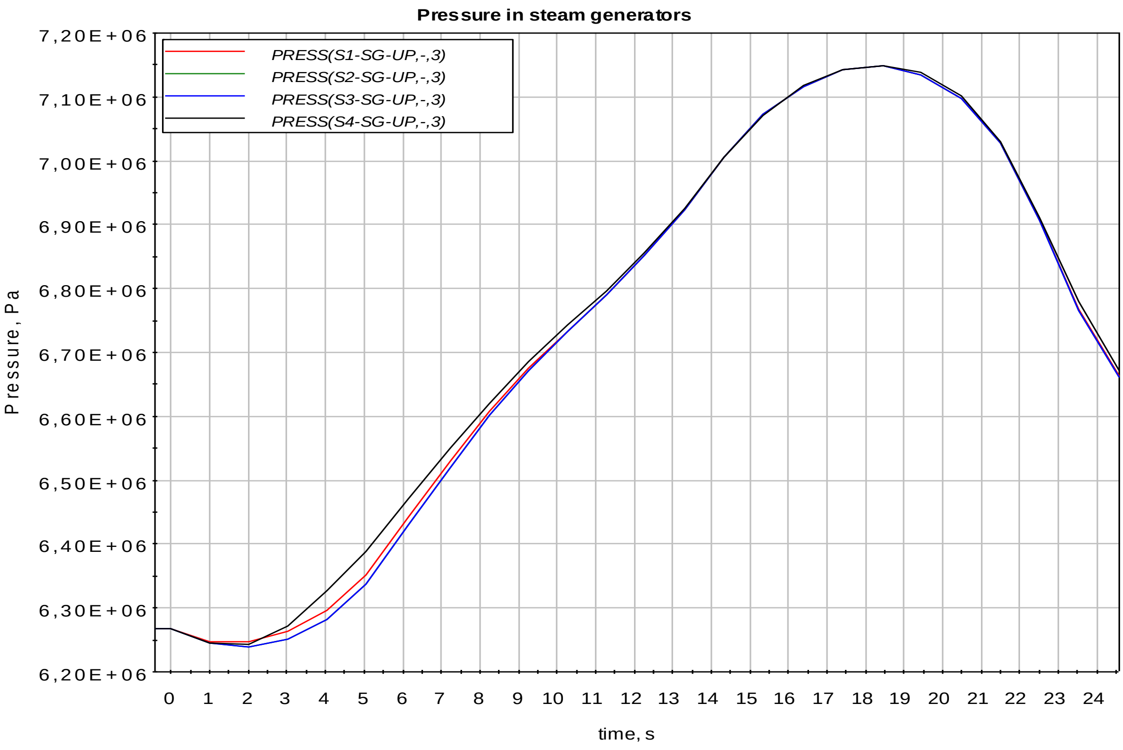

Figure 2.11 Pressure in steam generators

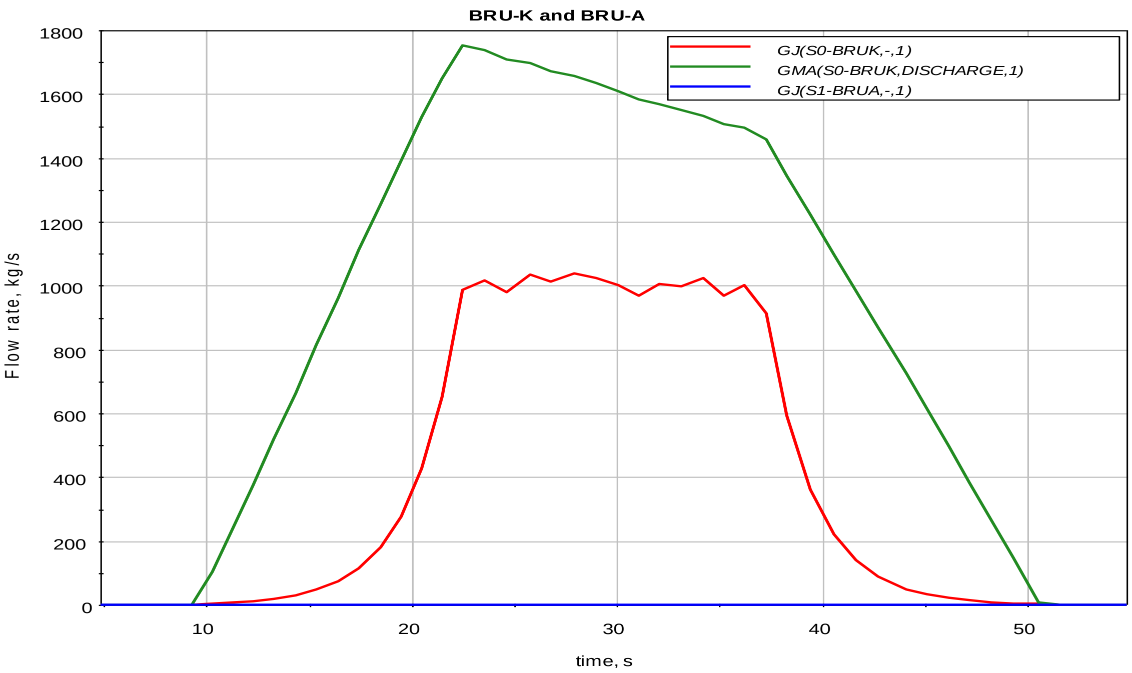

Figure 2.12 BRU-A and BRU-K operation
red curve: BRU-K mass flow rate; blue curve: BRU-A mass flow rate; green curve: critical discharge rate of BRU-K (= maximum possible mass flow through the valve)

The coolant from the pressurizer is drained in less than 20 seconds (cf. Figure 2.6). When the pressure at connection points of the hydro-accumulator pipelines falls below 5.88 MPa, the boric acid solution starts to flow from the hydro-accumulators (Figure 2.13 and Figure 2.14; note that the present ATHLET input deck does not contain neutron kinetics, but a GCSM-controlled power generation; consequently, an effect of the boron acid on the power generation cannot be observed here). The process of the reactor filling by the coolant starts at the 73th second and ends approximately at the 330th second when the valves in the hydro-accumulator injection lines close as the levels in the accumulators drop to 1.2 m, measured from the bottom of each vessel (Figure 2.14; the blue and the red curve do not coincide because of the different bottom elevations of the accumulators). Due to the fact that under the assumed BDBA conditions the active part of the emergency core cooling system (ECCS) does not work, the process of core overheating and boiling-out of the coolant from the reactor begins.

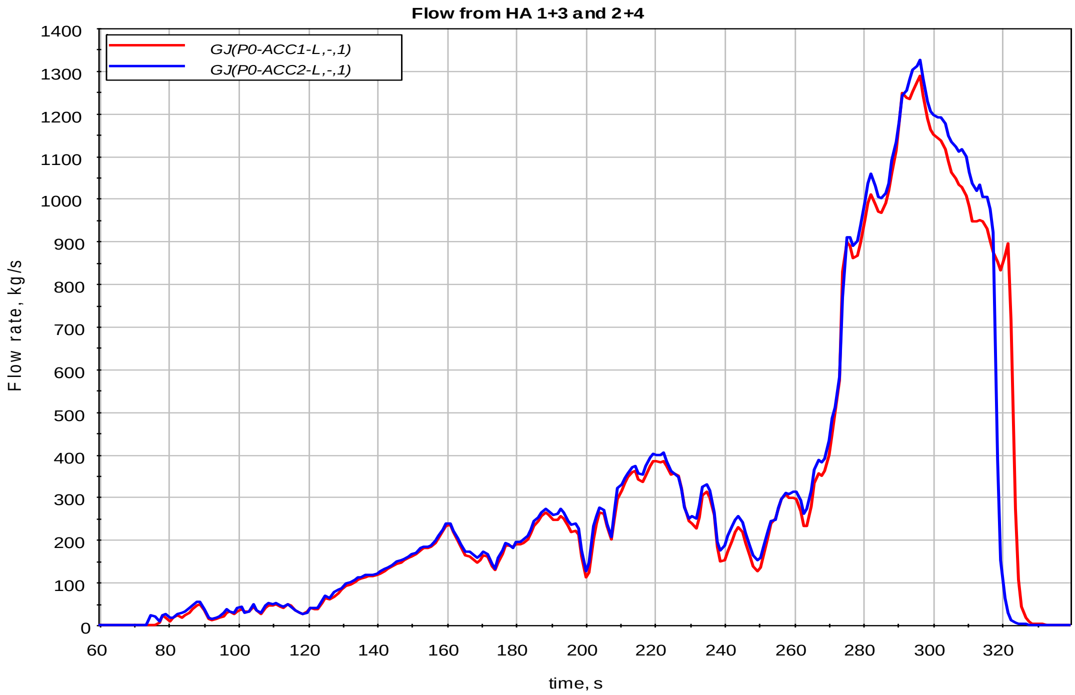

Figure 2.13 Hydro-accumulator mass flow

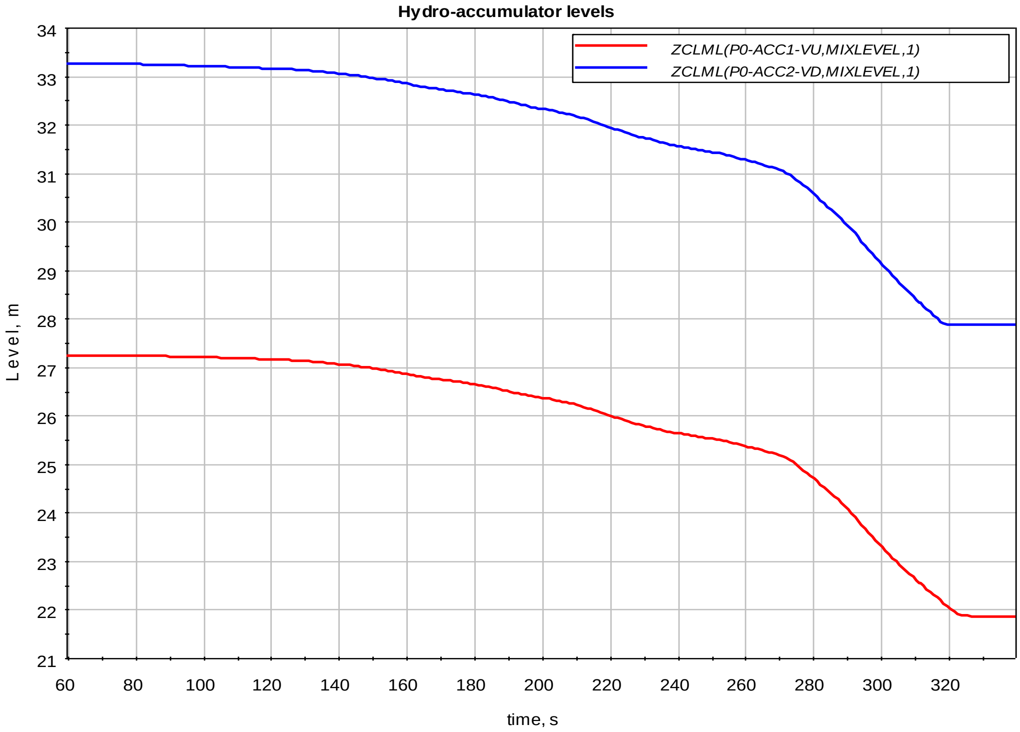

Figure 2.14 Hydro-accumulator levels (absolute height values)

After the MCPs are stopped, the reactor core is cooled by natural circulation, which almost completely stops after draining the U-tubes of the steam generator. Almost immediately after the formation of the leak, a short-term boiling of the coolant in the core occurs, then stops for a few seconds and starts again at 12 seconds (Figure 2.15). After the end of operating of the ECCS passive part (330 s), the mass fraction of steam in the coolant flow begins to increase. In Figure 2.16 and Figure 2.17, you can see that by the 450th second the u-tubes of the steam generator completely dry out.

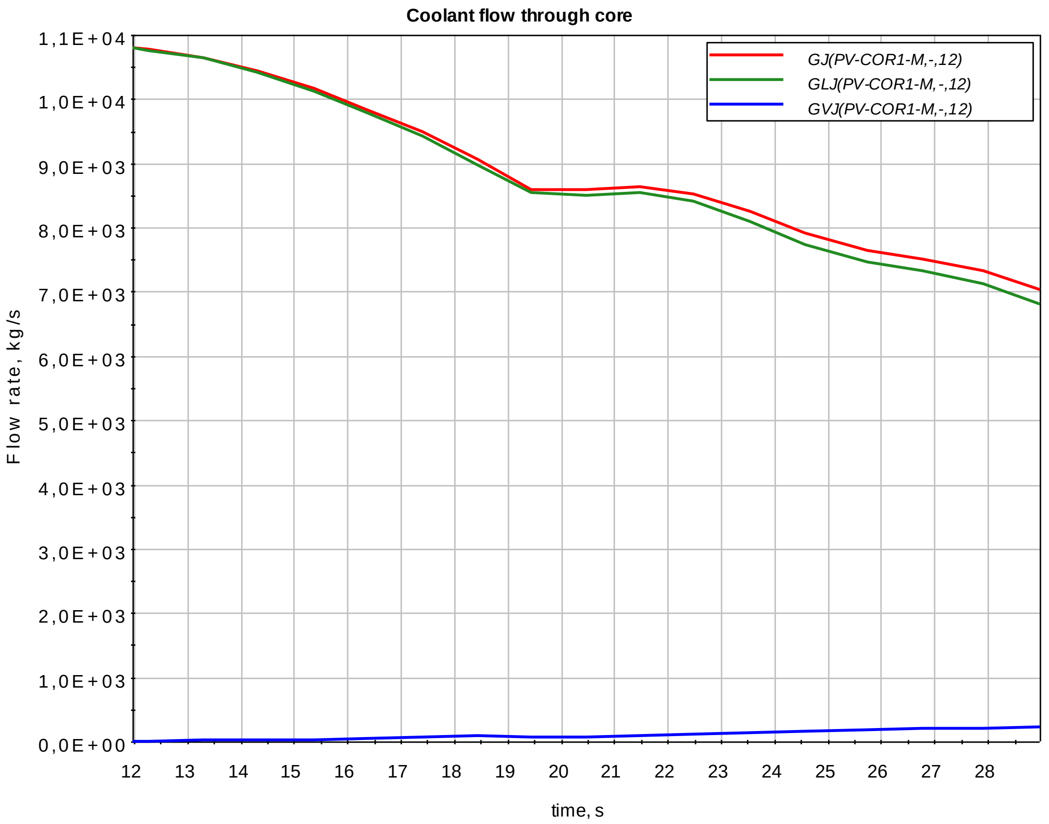

Figure 2.15 Coolant flow through core

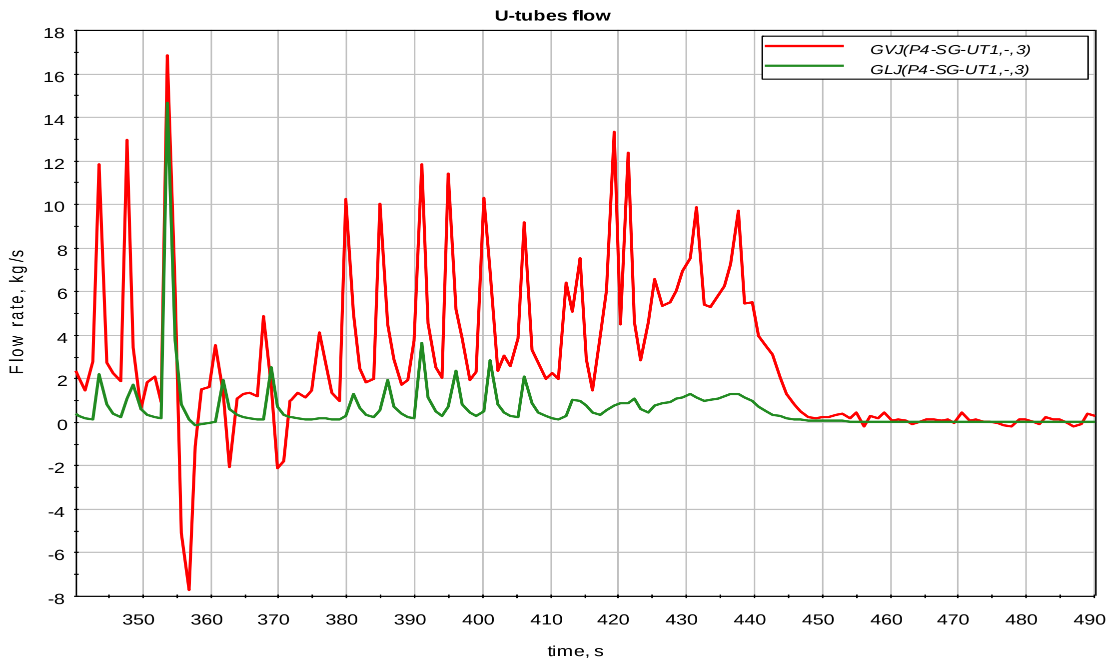

Figure 2.16 U-tubes liquid (green) and vapor (red) mass flow

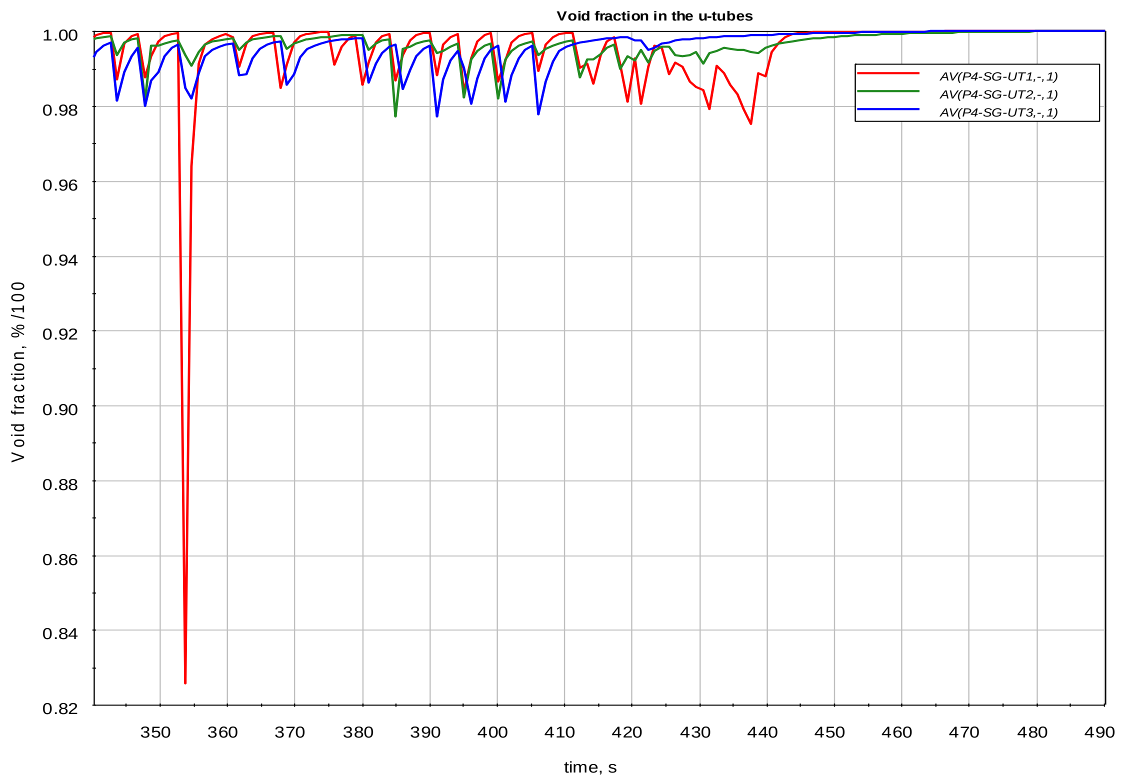

Figure 2.17 Void fraction in the three groups of u-tubes

Figure 2.18 shows that the mass fraction of steam in the upper part of the core from the 1350th second is 100%, which indicates the beginning of the core dehumidification process; the temperature of the steam begins to increase sharply (Figure 2.19). This process will inevitably lead to the occurrence of a steam-zirconium reaction and then melting of fuel rods.

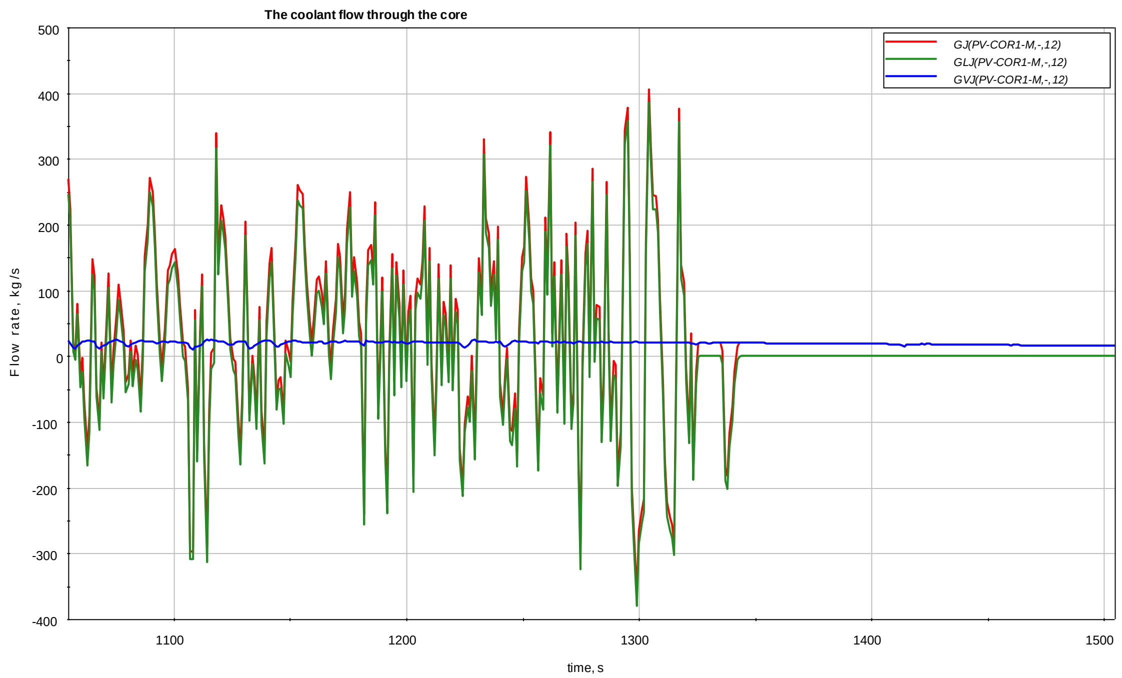

Figure 2.18 The coolant flow at the top of the core

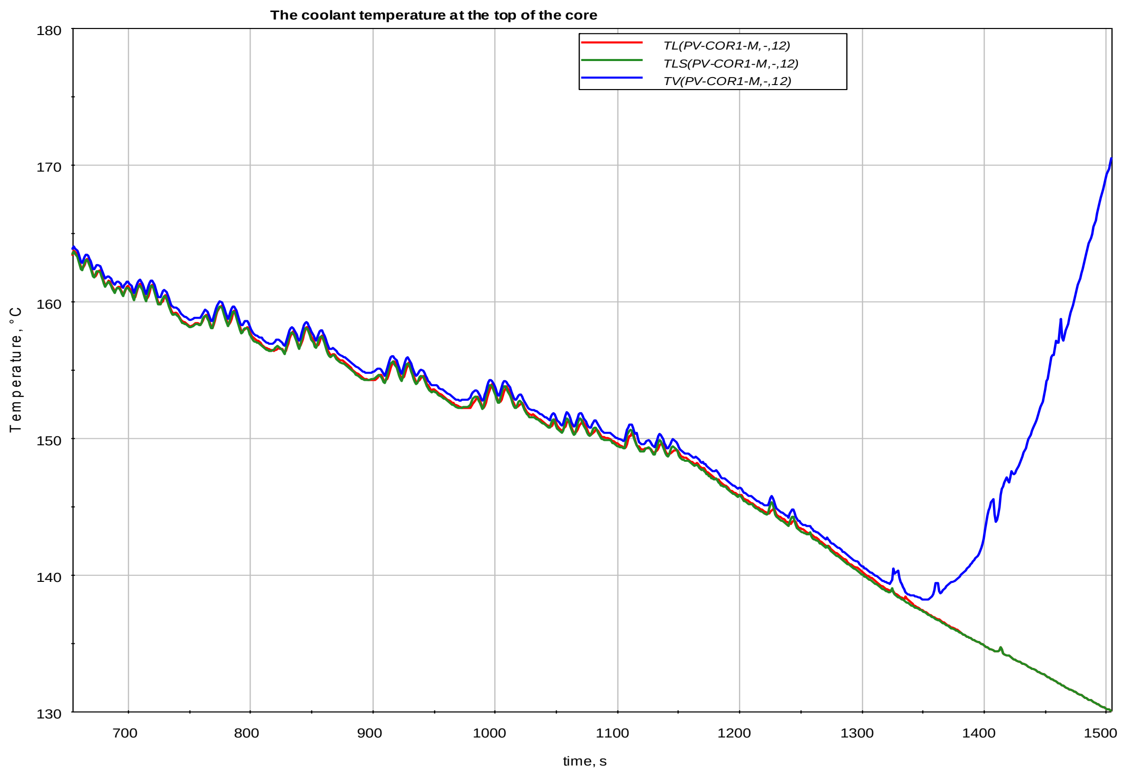

Figure 2.19 The coolant temperature at the top of the core

3. Design basis accident (DBA)

The second accident to be analyzed is the same loss of coolant accident as described in section 2 (LOCA in the cold leg close to the RPV nozzle with a 250 mm diameter of the leakage). However, this time the correct operation of the HPI and LPI systems is assumed.

Due to the fact that the HPI system injects cold boric acid solution into the reactor, the reactor pressure decreases slightly faster than in the BDBA case (Figure 3.1). In turn, this leads to an earlier start of the emptying of the hydro-accumulators (Figure 3.2).

Due to the supply of coolant by the LPI system, the u-tubes of the steam generators fall dry later than in the case of the BDBA, as seen in Figure 3.3 and Figure 3.4.

It can be seen from Figure 3.5 – Figure 3.7 that if from the 1020th second in the case of BDBA the core draining starts and the steam temperature rises (from 1060 s rapidly), then in the case of DBA, vaporization is insignificant, the coolant temperature is gradually reduced. Accordingly, the temperature of the fuel begins to increase rapidly in the BDBA case (which will lead to its destruction) whereas it slowly decreases in the case of DBA. Figure 3.8 shows the temporal progression of the fuel rod center temperatures at ½ of the core height (i.e. at a central position).

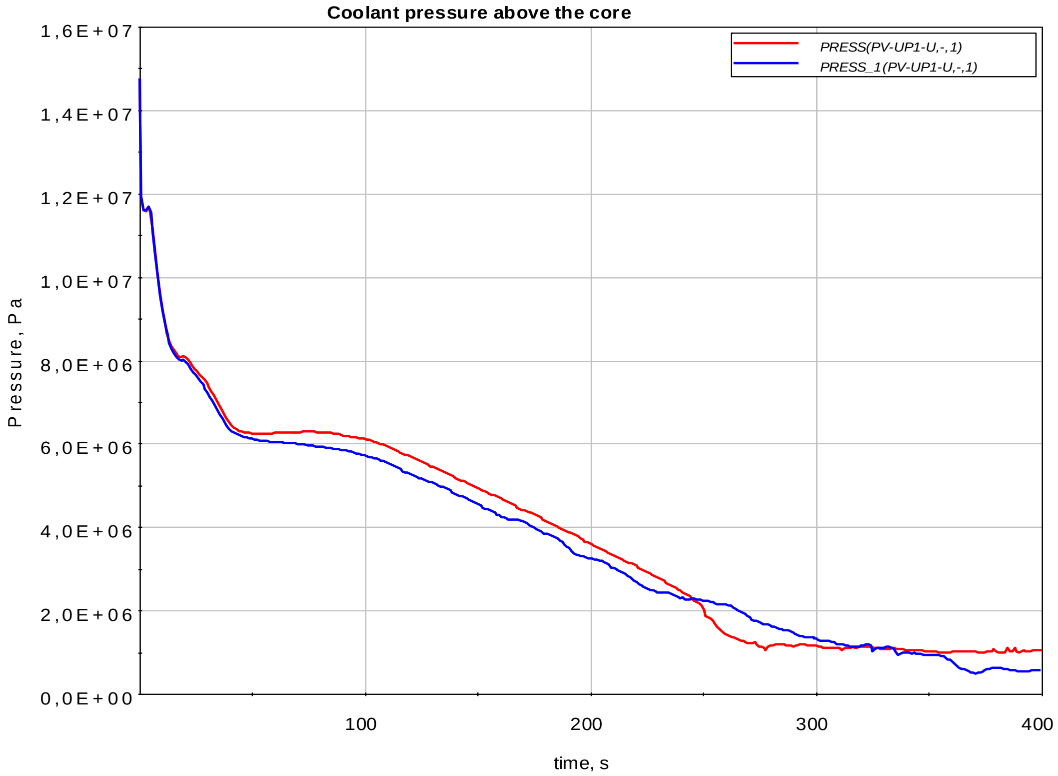

Figure 3.1 Coolant pressure above the core (PV-UP1-U, 1st case)
blue curve: DBA; red curve: BDBA

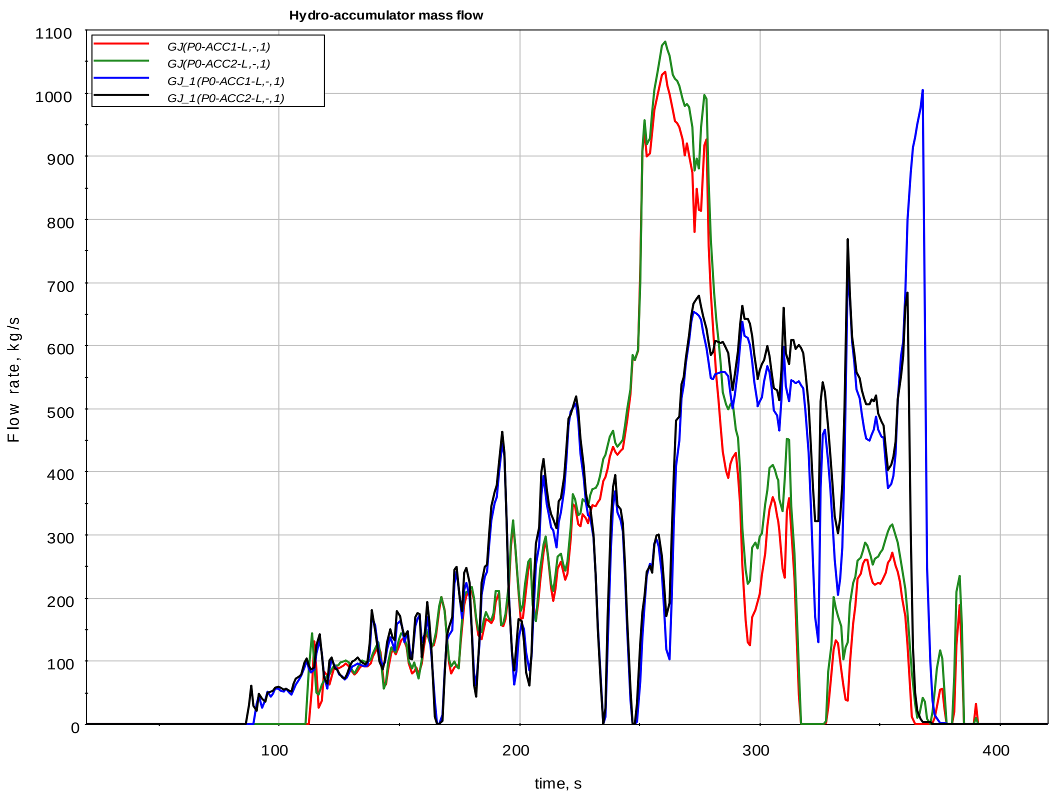

Figure 3.2 Flowrate from hydro-accumulators (1st case)
red/green curves: BDBA; blue/black curves: DBA

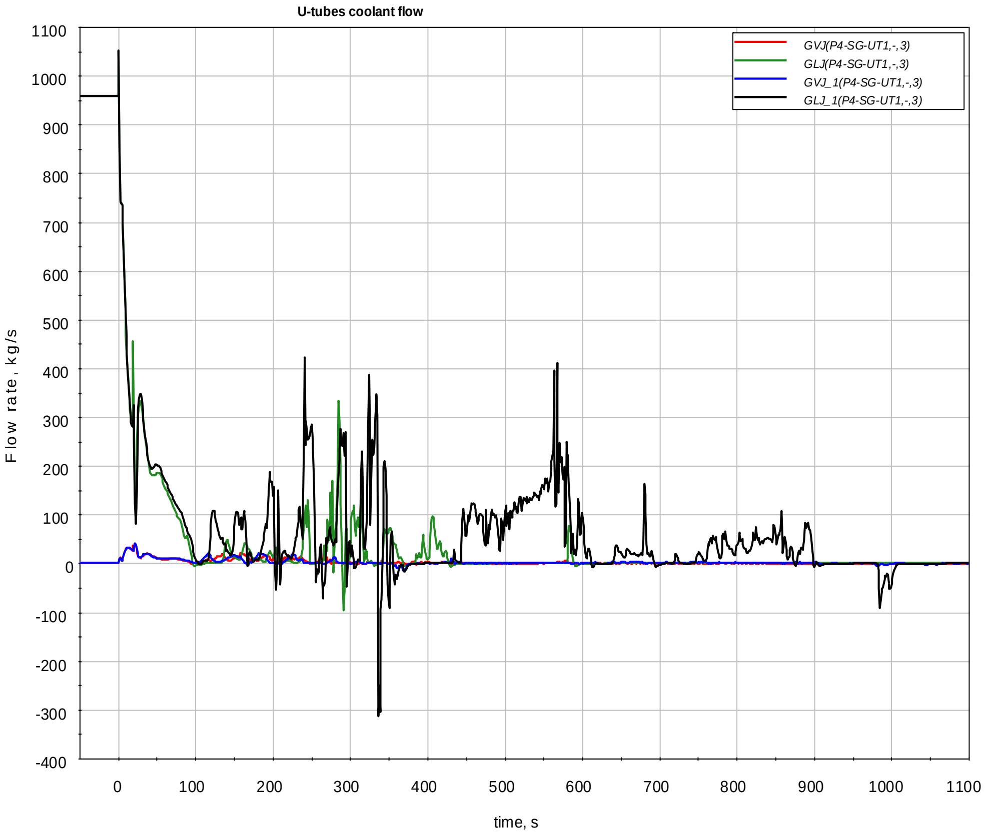

Figure 3.3 U-tubes coolant flow (1st case)
red curve: BDBA, vapor; green curve: BDBA, liquid;
blue curve: DBA, vapor; black curves: DBA, liquid

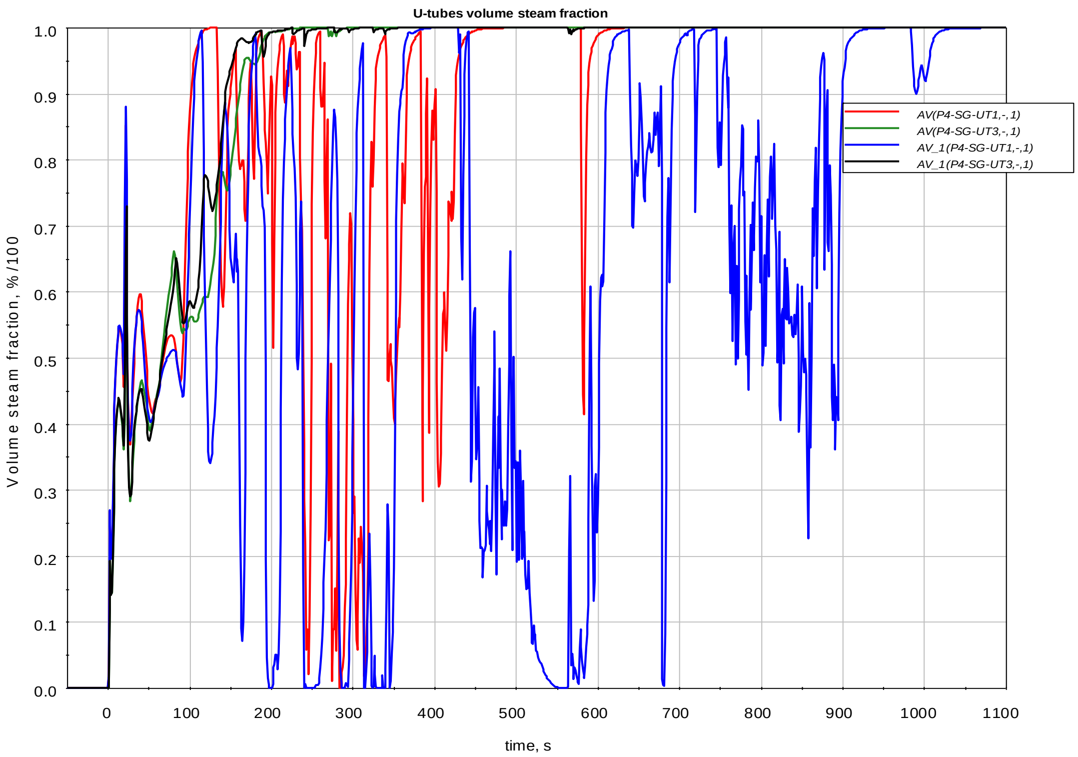

Figure 3.4 U-tubes volume steam fraction (1st case)
red/green curves: BDBA; blue/black curves: DBA

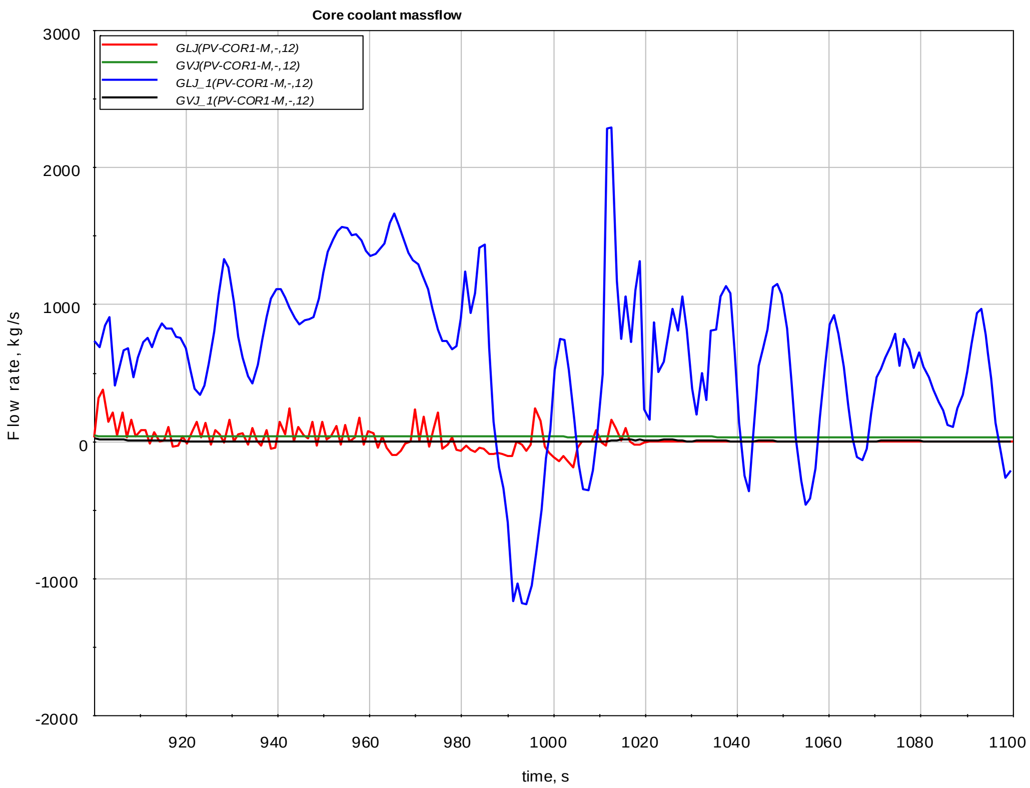

Figure 3.5 Core coolant mass flow (1st case)red/green curves: BDBA; blue/black curves: DBA

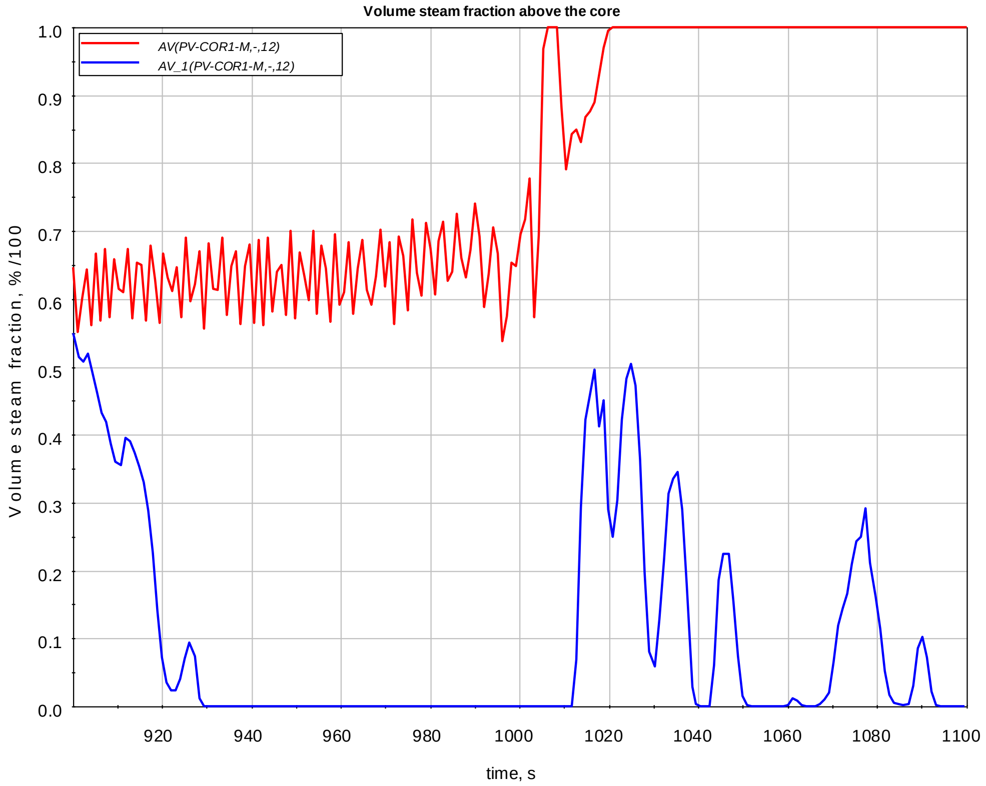

Figure 3.6 Volume steam fraction above the core (1st case) red curves: BDBA; blue curves: DBA

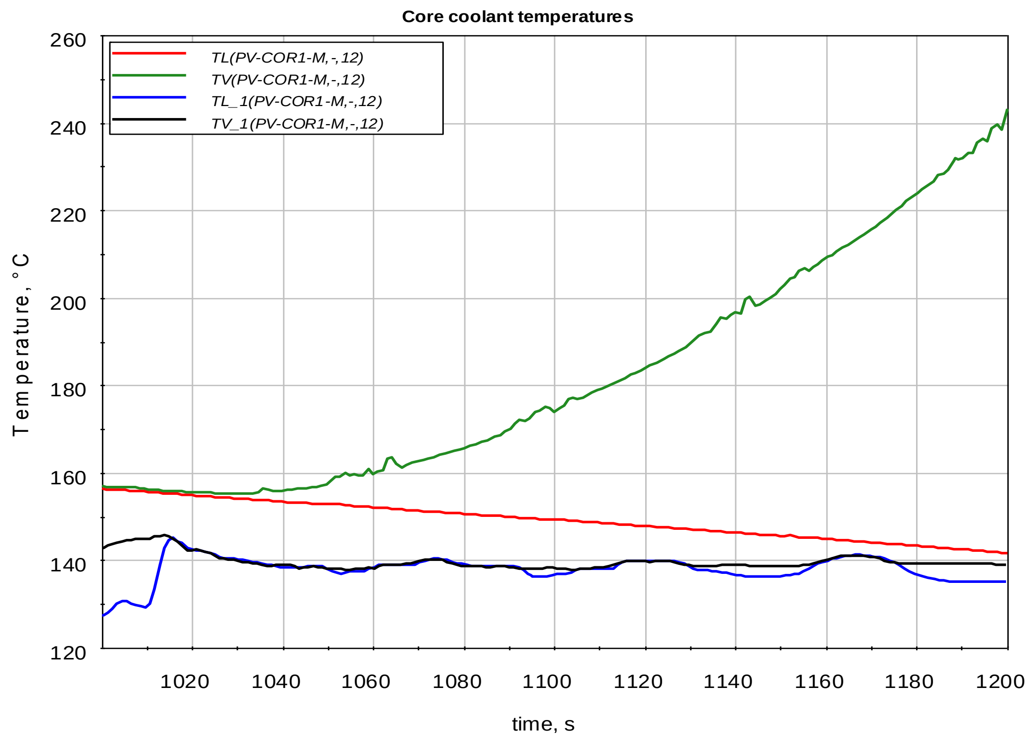

Figure 3.7 Core coolant temperatures (1st case)
green curve: BDBA vapor temperature; black curve: DBA vapor temperature

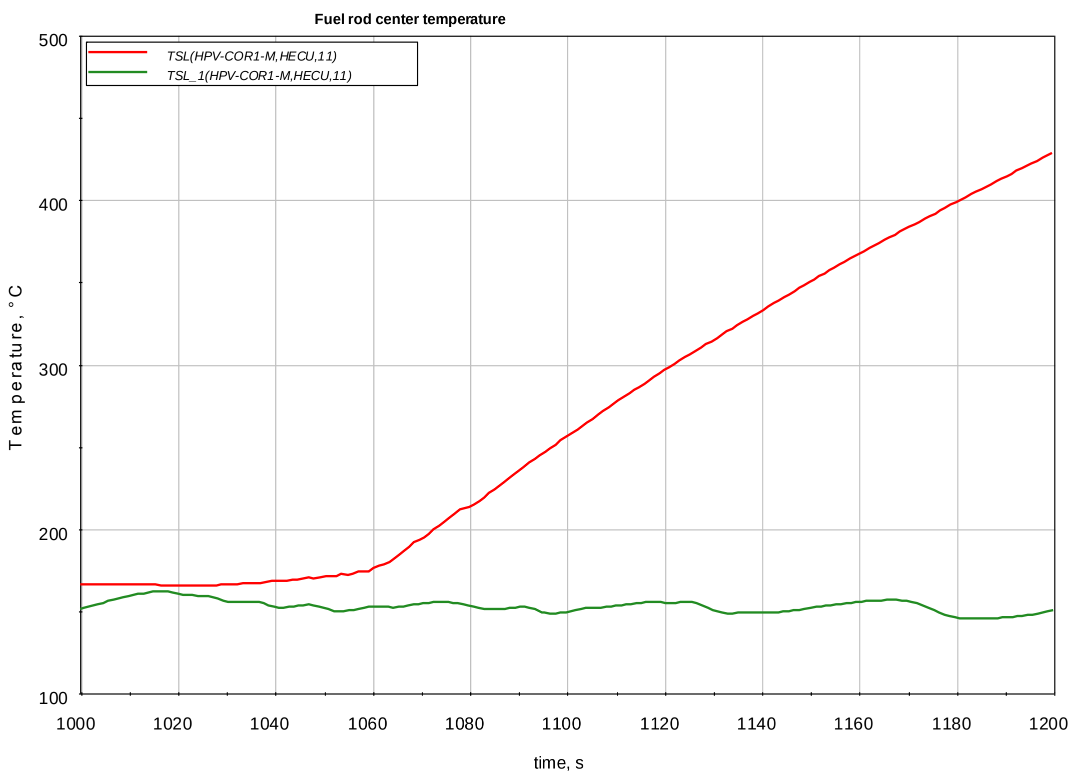

Figure 3.8 Fuel rod center temperature (1st case)
red curve: BDBA; blue curve: DBA

For scenario case 2 (pressurizer also attached to the 4th loop, decay heat calculated according to Way-Wigner formula, pump coast down curve described by an idealized exponential behavior), we can observe a similar behavior of the investigated values for the DBA simulation as in the 1st case (Figure 3.9 – Figure 3.11) while in the case of BDBA the beginning of the core draining and the steam temperature rising are shifted to 1350 s (see also Figure 2.18 and Figure 2.19). Accordingly, the rise of the central fuel temperature is shifted from 1060 s in the 1st BDBA case to 1587 s in the 2nd BDBA case (cf. Figure 3.8 and Figure 3.12).
Thus we have shown that, for the treated accident scenarios, the influence of the decay heat type and pump coast down characteristic on the core processes is significant for the BDBA progression whereas it is of minor importance for the DBA progression.

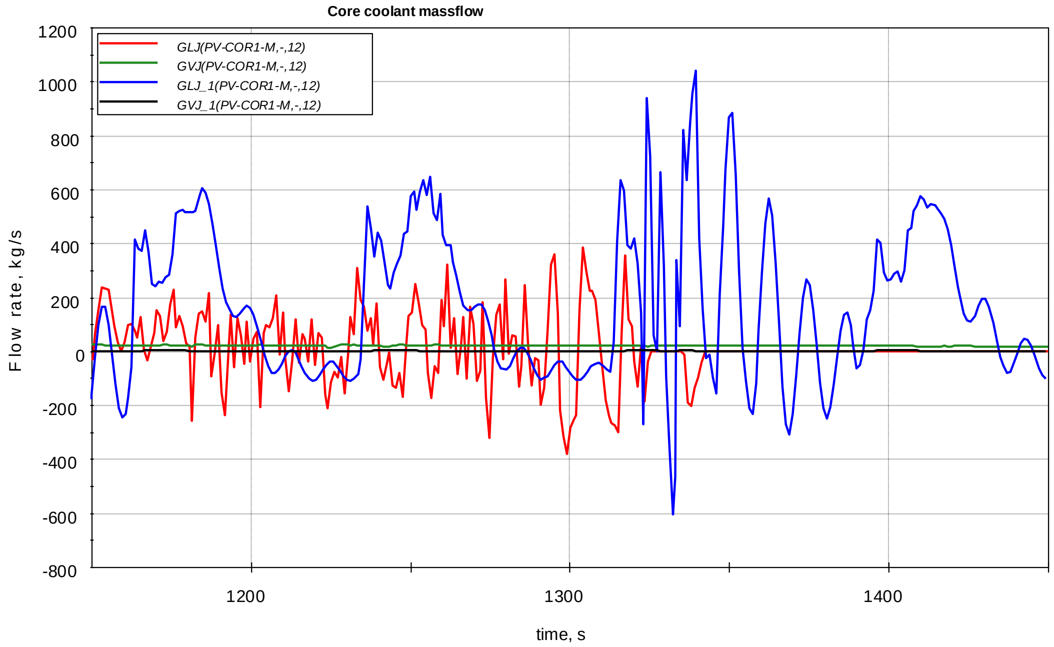

Figure 3.9 Core coolant massflow (2nd case)
red/green curves: BDBA; blue/black curves: DBA

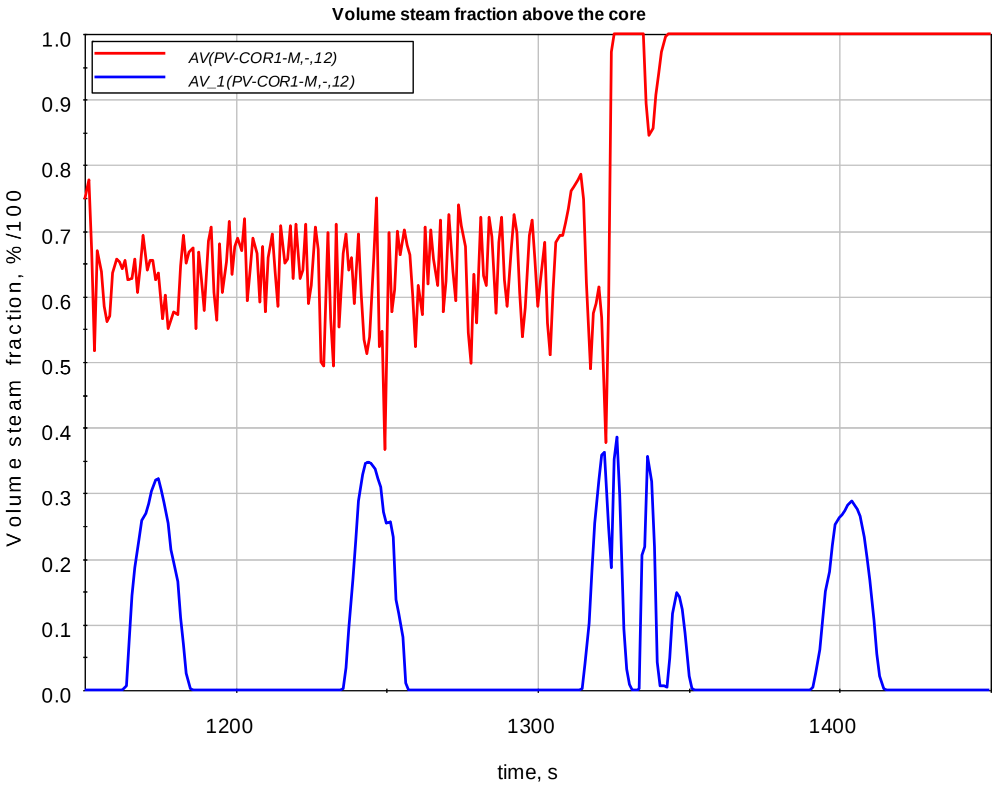

Figure 3.10 Volume steam fraction above the core (2nd case)
red curves: BDBA; blue curves: DBA

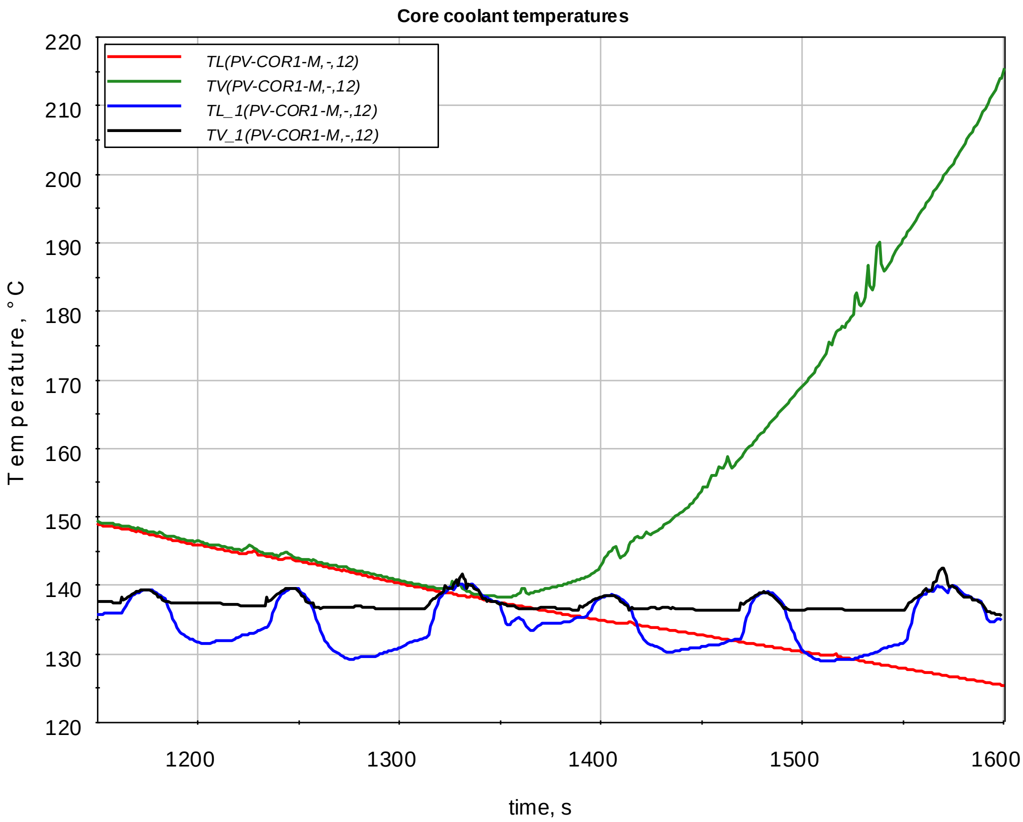

Figure 3.11 Core coolant temperatures (2nd case)
green curve: BDBA vapor temperature; black curve: DBA vapor temperature

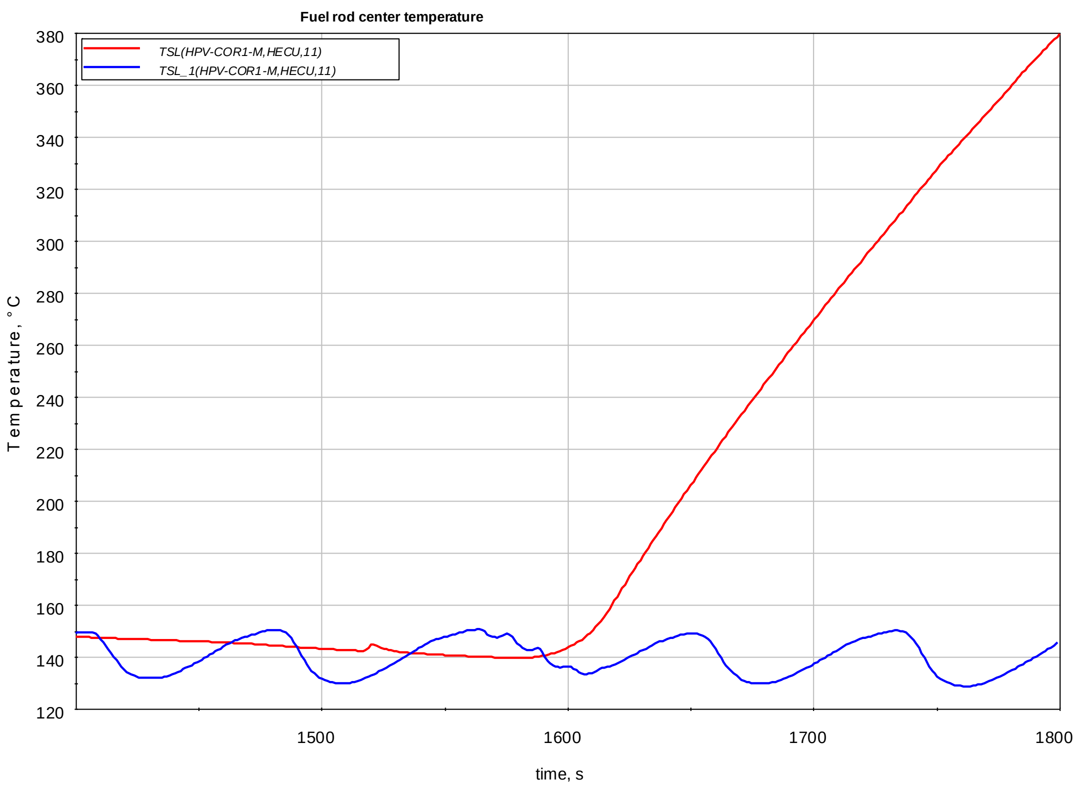

Figure 3.12 Fuel rod center temperature (2nd case)
red curve: BDBA; blue curve: DBA

4. Conclusion

The present report contains the analyses and description of the ATHLET simulations of two LOCA sequences, utilizing a generic VVER-1000 input deck:

1. Beyond design basis accident (BDBA): LOCA in the cold leg (close to the RPV nozzle), diameter 250 mm with failure of LPI and HPI systems.
2. Design basis accident (DBA): LOCA in the cold leg (close to the RPV nozzle), diameter 250 mm with operating LPI and HPI systems.

It was originally planned to investigate the sensitivity of the simulation results regarding variations in the input data by simulating three different cases:

1. Pressurizer attached to the 4th loop, decay heat and pump coast down curve as described in [1].
2. Pressurizer attached to the 4th loop, decay heat according to Way-Wigner formula, pump coast down curve as described by an idealized exponential behavior (cf. [2]).
3. The same as 2nd case, but the pressurizer is in 1st loop.

It was shown that the inclusion of active ECCS systems introduces significant differences in the quantitative characteristics of the parameters.

In particular

- because of the HPI system injecting cold boric acid solution into the reactor, the reactor pressure decreases faster in the DBA than in the BDBA case, which leads to an earlier start of the emptying of the hydro-accumulators;

- due to the supply of coolant by the LPI system, the u-tubes of the steam generators fall dry later than in the case of the BDBA;
- in the case of BDBA, the core draining starts and the steam temperature rises while in the case of DBA, vaporization is insignificant and the coolant temperature is gradually reduced. Accordingly, the temperature of the fuel begins to in-crease rapidly at a certain time in the BDBA case (which will lead to its destruction) whereas it decreases in the case of DBA.

Concerning the sensitivity of the simulation results regarding variations in the input data, changes of the decay heat and pump coast down characteristics had only a minor effect on the DBA simulations, but significantly changed the results of the BDBA calculations. In particular the beginning of the core drainage as well as the increase in steam temperature and the corresponding rise of the fuel temperature were considerably shifted to a later time when the input data was changed from the abovementioned case 1 to case 2.

Acknowledgments

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References

[1] A. Mikhalchuk et al.: Report on Input Data Base for Analyses on WER-1000 type NPP (Balakovo), Final Report, RISKAUDIT Report N° 87, February 1997, Tacis Programme, Contract No: 93-0151 - WW.91.03/03.01/B020

[2] V.A. Shaparau, E.G. Vashetko : Engineering Handbook for the ATHLET input deck of the generic VVER-1000. February 2018