

THERMAL HYDRAULIC ANALYSES FOR OPTIMIZATION OF HYDROACCUMULATOR PARAMETERS IN VVER-440

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Abstract

The passive ECCS system of VVER-440/213 according to the original Russian design consisted of 4 hydroaccumulators (HA) with nitrogen at pressure 6.0 MPa. In 90ties, the HA pressure in some VVER-440 was reduced to 3.5 MPa. This design modification was firstly done at NPP Dukovany (1998) in the Czech Republic and was based on TH analyses performed at UJV Rez. This pilot example was later followed by other VVER-440 NPP's, like Finish Loviisa, Hungarian Paks and Slovak Bohunice. Lastly the UJV Rez has prepared another step in optimization of HA parameters - increase of HA level and extension of allowed margins for HA pressure and level. The paper documents major steps in VVER-440 optimization and relevant thermal-hydraulic analyses including the latest work.

Introduction

The VVER is a Russian version of Pressurized Water Reactor (PWR). The first versions of VVER were built in Russia in late 60ties and were not equipped with hydroaccumulators.

A standard PWR-like concept of Emergency Core Cooling System (ECCS) consisting of 4 hydroaccumulators, 3 trains of High Pressure Injection System (HPIS), and 3 trains of Low Pressure Injection System (LPIS) was firstly incorporated in VVER-440/213 type in 70ties and applied at numerous NPP's in European part of former Soviet Union, the former Czechoslovakia, Hungary, and other countries. Special role in this evolution of VVER design played the Loviisa NPP.

The nitrogen pressure in HA was 6.0 MPa according to the original design of VVER-440/213. This HA pressure is quite high, especially when compared to nominal pressure in reactor coolant system 12.3 MPa or when compared to steam generator safety valves opening pressure 5.8 MPa (see Table 1 below).

Therefore a study on optimization of HA pressure was initiated in the Czech Republic in 1993 [1-3]. The Dukovany NPP operating four units with VVER-400/213 reactors ordered the study and necessary analyses in the Nuclear Research Institute (UJV) Rez. The two principal objectives of the study were to increase efficiency of HA injection for core cooling in loss-of-coolant accident (LOCA) and to improve conditions for operator mitigation primary-to-secondary leaks (PRISE).

Lastly, another step in optimization of HA parameters was prepared in cooperation of NPP Dukovany and UJV Rez – the increase of HA level and extension of allowed margins for HA pressure and level [6, 7].

1. Description of VVER-440/213 hydroaccumulator system – original design

The system of 4 hydroaccumulators (HA) and their injection lines creates the passive part of the Emergency Core Cooling System. The pressurized nitrogen under 6.0 MPa ensures forcing out the borated water from the HA into reactor vessel in case of primary pressure decrease.

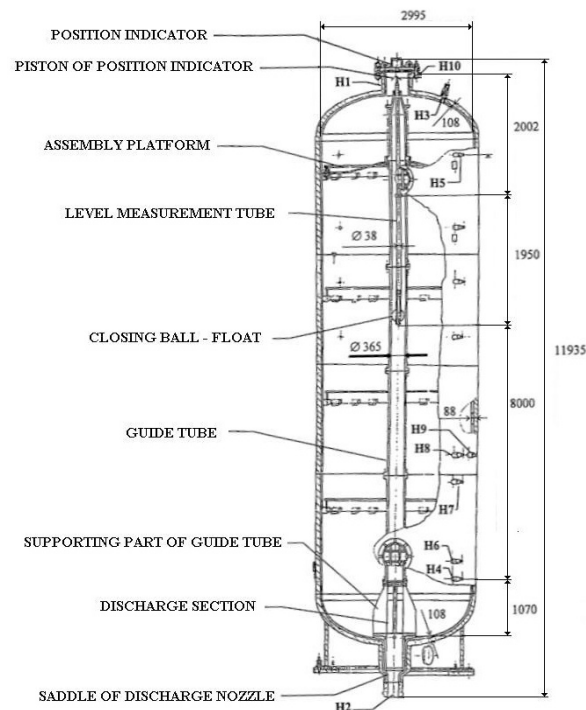


Figure 1 Layout of VVER-440 hydroaccumulator

Two HA's are connected to reactor upper plenum (UP). In front of the HA lines connection to UP, there is a flow shield to protect UP internals. The other two HA's are connected to reactor downcomer (DC). There are 3 flow baffles around the HA lines connections in the DC top, designed to force HA flow downward and to suppress "ECCS bypass" during large-break LOCA (LBLOCA).

Each HA injection line contains 2 check valves and 1 isolation valve. At the HA lines, there are also connections of discharge lines of 2/3 LPIS (connection is done between the isolation valve and the second check valve). To prevent inflow of nitrogen into Reactor Coolant System (RCS), the HA injection is stopped by a float valve as soon as the level drops to approximately 0.5 m.

2. Comparison of ECCS characteristics between VVER and PWR

In the table below, the main parameters of Emergency Core Cooling System and the relevant system parameters of several VVER's and western PWR's are compared.

Table 1 Comparison of system and ECCS parameters of various PWR's

	Unit	VVER-440/213	VVER-1000	Sizewell-B (Westinghouse)	KWU-1300 Konvoi	EPR-1600
Basic pressure characteristics of NPP:						
- primary pressure	MPa	12.3	15.7	15.5	15.8	15.5
- secondary pressure	MPa	4.7	6.3	6.9	6.4	7.8
- SG safety valves opening/closing press.	MPa	5.8/4.9	8.2/8.0	8.6/8.3	8.8/8.3	10.1/9.4
HPIS (MPIS) pumps:						
- number	-	3	3	4	4	4
- shutoff head	MPa	14.3	10.8	11.8	11.1	9.5
- normal flow rate	kg/s	37.5	56.0	110.0	51.0	45.0
LPIS pumps:						
- number	-	3	3	2	4	4
- shutoff head	MPa	0.7	2.6	1.7	1.2	2.2
- normal flow rate	kg/s	111.0	222.0	260.0	470.0	165.0
Hydroaccumulators:						
- number	-	4	4	4	8	4
- pressure	MPa	6.0	6.0	4.5	2.6	4.6
- water volume	m ³	40	50	40	34	38
- gas volume	m ³	30	10	17	11	17
- ratio gas/total volume	-	0.43	0.17	0.30	0.24	0.31
Points of ECCS injection (cold leg, hot leg, upper plenum, downcomer)	-	CL, HL, UP, DC	CL, HL, UP, DC	CL	CL, HL	CL, HL

Specific features of VVER-440/213 HA design are the high pressure in hydroaccumulators comparing to the primary pressure, secondary pressure and set-points of steam generator safety valves (SG SV) and, on the other side, the low shut-off head of LPIS pumps.

Also the high ratio of gas volume to total volume of HA is unique. It would lead to very fast HA injection into RCS in case of medium- and large-break LOCA. Another specific feature of HA design are the flow baffles in the top of reactor downcomer.

Further characteristics of ECCS design in VVER-440/213 are the high shut-off head of HPIS pumps (comparing to RCS pressure) and direct reactor injection of HA's and 2/3 LPIS.

3. Objectives of HA optimization

The initiative to optimize VVER-440 hydroaccumulator parameters arose in early 90ties at Dukovany NPP. There were two major objectives of this effort:

1. To improve boundary conditions for operator during mitigation of primary-to-secondary leak accidents (to enable the operator decreasing RCS pressure below SG SV set-points without disturbances caused by HA injection).
2. To get better efficiency of HA injection in LOCA (mainly in intermediate and large break LOCA - longer time margin for operator in case of failure of all active ECCS, improved system behavior in case of failure of HPSI or LPSI, reduction of time period between HA injection end and LPIS injection start, etc.).

In the latest effort in field of optimization of VVER-440 HA parameters (2009-2010), the major objectives were as follows:

3. To extend the allowed range of HA pressure and level. Increase of HA level. Increase of limiting primary pressure for isolation of HA. Thorough application of HA parameters uncertainties into relevant safety analyses.

4. Computer codes and models used for HA optimization analyses

The major volume of calculations for NPP Dukovany HA optimizations was performed with help of advanced thermal hydraulic computer code RELAP5, versions ranging from MOD2.5 to MOD3.3. Some additional analyses were made with the ATHLET code.

The TH computer code RELAP5 has been widely assessed in UJV Rez. Data from integral test facilities PMK (Hungarian), PACTEL (Finish), RVS (Czech), ISB and PSB (Russian) as well as measurements from NPP have been used during code implementation, assessment and users qualification. Several tens of tests have been analyzed either as blind-tests or as post-test analysis. UJV Rez participated also in lots of international projects such as International Standard Problem (ISP), Russian Standard Problem (RSP), IAEA projects (SPE) etc.

As for the input model of VVER-440 for RELAP5, in 90ties a relatively simple 3-loop model was prepared to represent 6-loop configuration of VVER-440 (model with one single, one double, and one triple loop). Later on, a more detailed 6-loop model was prepared – see the nodalization scheme in Figure 2 below. Besides the modeling of all 6 primary loops, lots of other improvements was done in the model such as more detailed modeling of ECCS, finer nodalization of reactor downcomer, more layers representing SG tubing etc.

As the most important postulated accidents affected by hydroaccumulators are the loss-of-coolant accidents (LOCA), special attention was paid to reactor downcomer nodalization (2/4 HA are connected directly to DC). The analyst should reflect existence of flow baffles in DC top nodalization. The lower sections of DC are modeled either in 1-D or in 2-D way.

Another important part of the model strongly influencing effectiveness of hydroaccumulator injection is the upper plenum of reactor (2/4 HA are connected directly to UP). A 3-channels

nodalization of UP was applied, not to flood equally all core channels, what would be unrealistic and non-conservative.

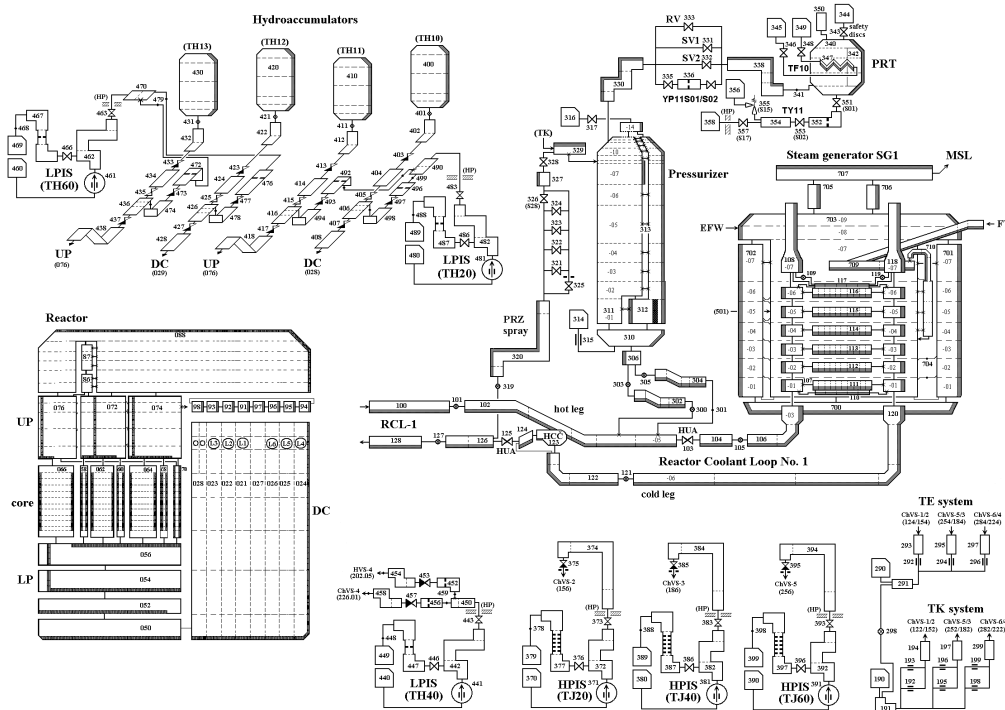


Figure 2 Input model of VVER-440 for RELAP5 (only 1 of 6 modeled loops depicted)

5. The first phase of HA parameters optimization at NPP Dukovany

The first project focused on optimization of parameters of VVER-440 hydroaccumulators was initiated by NPP Dukovany in 1993. The primary motivation was to increase efficiency of HA injection for core cooling in loss-of-coolant accident and to improve conditions for operator mitigation of primary-to-secondary leaks. The necessary thermal-hydraulic analyses were ordered at the Nuclear Research Institute (UJV) Rez.

The first set of analyses and proposal on HA optimization was elaborated and supplied to NPP Dukovany at the end of 1993. The first proposals were oriented not only to HA pressure reduction, but also to usage of 2-pressure configuration [1, 2]. This solution would be very efficient in LOCA, but due to potential technological and operational problems, these proposals were not accepted.

Continuation of analytical work and expert discussion between UJV Rez, NPP Dukovany and also the Czech regulatory body (SUJB) resulted in 1995 in the **final proposal of HA pressure reduction from 6.0 MPa to 3.5 MPa** [2, 3]. This design modification was **applied at NPP Dukovany in 1998**.

The TH analyses performed in 1993-1995 can be divided into the following groups:

- Analysis of spectrum of LOCA with no active Safety Injection (SI) and 4 HA's with various pressures.
- Analysis of spectrum of LOCA with no active SI and 4 HA's with various levels.
- Analysis of spectrum of LOCA with no active SI and 4 HA's with various temperatures.
- Analysis of spectrum of medium-break and large-break LOCA with no LPIS, 1/3 HPIS and 2 HA's at various pressures.
- Analysis of small-break LOCA with no HPIS, 1/3 LPIS and 2 HA's at various pressures.
- Safety analyses with final modification of HA pressure.

Examples of results from these TH analyses can be seen in Figure 3 and Table 2 below. At first, the major HA parameters - pressure, level, and temperature - were evaluated. It was found out, that changes in HA level and temperature do not bring any strong improvement of LOCA results. So in the first phase of HA optimization, it was decided to concentrate on HA pressure optimization.

As for the influence of HA pressure on the time to core uncover and fuel overheating, the most efficient was the two-pressure modification "2x4.5 MPa (UP) + 2x2.5 MPa (DC)". From the single pressure modifications, the best results were obtained with the "4x3.5 MPa" HA pressure modification. Also the other alternatives with single reduced pressure (4x4.5 MPa, 4x2.5 MPa) showed mostly better performance than original HA with 4x6.0 MPa.

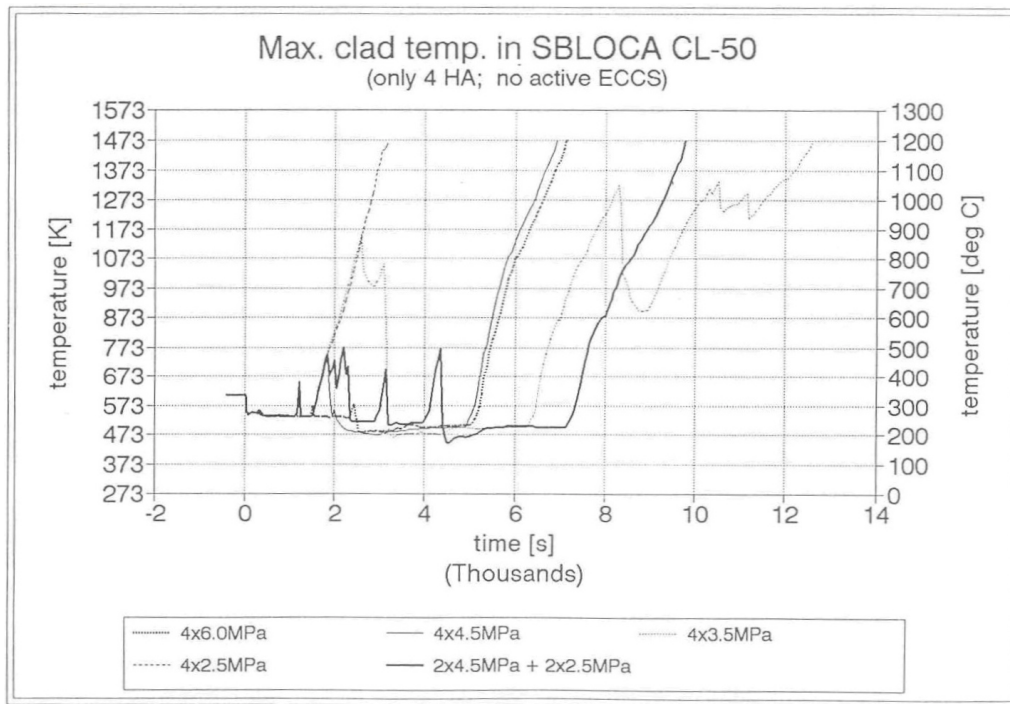


Figure 3 Maximal clad temperature in analysis of break D50 with 4 HA and none active ECCS

Table 2 Time of core overheating (1200 °C) in selected LOCA with only 4 HA (no active SI) with various HA pressure

	<i>No ECCS (no HA)</i>	Only 4 HA at 6.0 MPa	Only 4 HA at 4.5 MPa	Only 4 HA at 3.5 MPa	Only 4 HA at 2.5 MPa	Only 2 HA at 4.5 MPa and 2 HA at 2.5 MPa
Break in cold leg:						
D50mm	<i>3173 s</i>	7151 s (100%)	6937 s (-3%)	12588 s (+76%)	3173 s (-56%)	9771 s (+37%)
D90mm	<i>1660 s</i>	3675 s (100%)	3602 s (-2%)	4196 s (+14%)	4516 s (+23%)	6475 s (+76%)
D150mm	<i>856 s</i>	1970 s (100%)	2587 s (+31%)	2824 s (+43%)	3136 s (+59%)	3226 s (+64%)
D300mm	<i>447 s</i>	1297 s (100%)	1611 s (+24%)	1500 s (+16%)	1542 s (+19%)	1495 s (+15%)
DEGBR 2xD500	<i>279 s</i>	957 s (100%)	1151 s (+20%)	1141 s (+19%)	1157 s (+21%)	1135 s (+19%)
Break in hot leg:						
D150mm	<i>1235 s</i>	3862 s (100%)	5102 s (+32%)	5239 s (+36%)	5875 s (+52%)	5083 s (+32%)
D300mm	<i>602 s</i>	2209 s (100%)	2277 s (+3%)	2436 s (+10%)	2630 s (+19%)	2537 s (+15%)
DEGBR 2xD500	<i>335 s</i>	1487 s (100%)	1577 s (+6%)	1588 s (+7%)	1687 s (+13%)	1580 s (+6%)
Average change of time margin to core overheat comparing to original HA pressure:			+13.9%	+27.6%	+18.8%	+33.0%
Order based on the maximal time margin:		5.	4.	2.	3.	1.

Major benefits of the HA pressure reduction from 6.0 MPa to 3.5 MPa are as follows:

- (+) **Improved boundary conditions for the operator during mitigation of primary-to-secondary leak accidents** (operator can decrease system pressure below SG SV range without disturbances caused by HA injection).
- (+) **Better efficiency of HA injection in LOCA** (mainly in intermediate and large break LOCA - longer time margin in case of all active ECCS failure, improved system behavior in case of failure of HPSI or LPSI, reduction of period between HA injection end and LPIS injection start)
- (+) **Reduced PTS risk** for reactor pressure vessel (injection of HA into DC at lower primary pressure and lower primary temperature - i.e. smaller ΔT 's in reactor DC).
- (+) **Easier operation of HA** during reactor shutdown and start-up (no more needed HA pressure reduction 6.0 $\rightarrow$ 3.5 MPa during shutdown).
- (+) **Reduction of time with HA disconnected from RCS** during reactor shutdown and start-up (with original HA pressure, the HA used to be disconnected for RCS pressure below 7.0 MPa; with modified HA, the disconnection is performed at 4.5 MPa).

There are also certain deficiencies connected with HA pressure decrease from 6.0 to 3.5 MPa:

- (-) In some small break LOCA with HPSI failure, there is reduced time margin before operator actions (e.g. operator started aggressive cool-down by help of steam dump to condenser).
- (-) Lower final pressure in HA after injection end (originally = 2.5 MPa, now = 1.5 MPa) can lead to worse sealing of HA by the float valve - slightly increased risk of nitrogen inflow into RCS.

6. Overview of HA optimization in countries operating VVER-440

Also some other NPP's with VVER-440/213 initiated at the end 90ties projects focused on optimization of hydroaccumulator and other ECCS systems [4-6]. The chronological overview of HA optimization at VVER-440's looks so far as follows:

1. NPP Dukovany, The Czech Republic, 1998: Reduction of HA pressure 6.0 $\rightarrow$ 3.5 MPa.
2. NPP Loviisa, Finland, 2000: Reduction of HA pressure (5.5 $\rightarrow$ 3.5 MPa) and increase of HA level (equivalent volume increase 40 $\rightarrow$ 50 m³).
3. NPP Paks, Hungary, 2006: Reduction of HA pressure (6.0 $\rightarrow$ 3.5 MPa) and increase of HA level (6.0 $\rightarrow$ 7.1 m).
4. NPP Jaslovske Bohunice, Slovakia, 2006: Reduction of HA pressure (6.0 $\rightarrow$ 3.5 MPa).

As far as we know, at the two units with VVER-440/213 in Ukraine (Rovno) and the two units in Russia (Kola), the HA pressure is kept at its original level 6.0 MPa.

7. Role of experimental data in assessment of computer code and model used and in verification of HA pressure reduction

Besides the extensive RELAP5 computer code assessment in UJV Rez against integral test facilities (see above – chapter 4), we assessed the code and input model also against measured data from NPP Dukovany. Among others against HA blowdown test, performed during unit shutdown. The measured and calculated HA parameters (pressure and level) were in very good agreement [2].

Lastly, the reduction of HA pressure at VVER-440 from 6.0 MPa to 3.5 MPa has been verified at integral test facilities PACTEL and PMK, for example in IMPAM-VVER project in 2003, where the test T2.3 with reduced HA pressure was performed as the counterpart test at both PACTEL and PMK facility [5].

8. New analyses for increase of HA level and extension of allowed margins of HA parameters at NPP Dukovany

The TH analyses performed lastly in “the second phase” of HA optimization at Czech NPP with VVER-440/213 [7] have the following 3 objectives:

- Extend allowed margins for HA pressure and level (currently the allowed range of HA level is 6.2 ± 0.2 m and the allowed range of HA pressure is 3.5 ± 0.2 MPa).
- If possible, increase and optimize HA level (currently the nominal HA level is 6.2 m, what corresponds to 41.5 m³ of liquid).
- Increase limiting primary pressure for isolation of HA's during NPP shutdown (currently the HA should be connected/disconnected by RCS pressure 4.5 MPa).

The increase of HA level is limited by elevations inside the HA, especially by the nominal position of the flange at the level measurement tube (see Figure 1). The HA level should not be above the flange, otherwise water could penetrate the measurement tube and the closing ball. And consequently this floating level measurement device would sink to the bottom of HA and close the outlet nozzle. The limiting level in case of NPP Dukovany is 7.75 m, so the maximal HA level including uncertainty of measurement should not exceed this value.

Based on analyses of various LOCA's, expert judgment and discussions with NPP experts, **the finally proposed new margins of HA pressure and level** are as follows:

- HA pressure (abs.): **3.5 ± 0.3 MPa**;
- HA level (from bottom): **6.5 ± 0.3 m**.

In this way, the allowed range of HA pressure would be increased from 0.4 to 0.6 MPa. And similarly, the allowed range of HA level would be increased from 0.4 m to 0.6 m.

The increased ranges of allowed HA levels and mainly pressure are important for operators during start-up and shutdown of the system, when the changes of HA temperature (in range

20-60 °C) results in substantial changes of HA pressure. The nitrogen pressure change during startup can be 0.55 MPa, if operator does not release part of nitrogen out of HA.

In the safety analysis, the analyst should add to the newly proposed margins of HA parameters (pressure 3.5 ± 0.3 MPa, level 6.5 ± 0.3 m) also the uncertainties for pressure measurement (0.2 MPa) and level measurement (0.16 m). Then the minimal and maximal values of HA pressure and level in safety analysis should be 3.0 – 4.0 MPa, and 6.04 – 6.96 m, respectively.

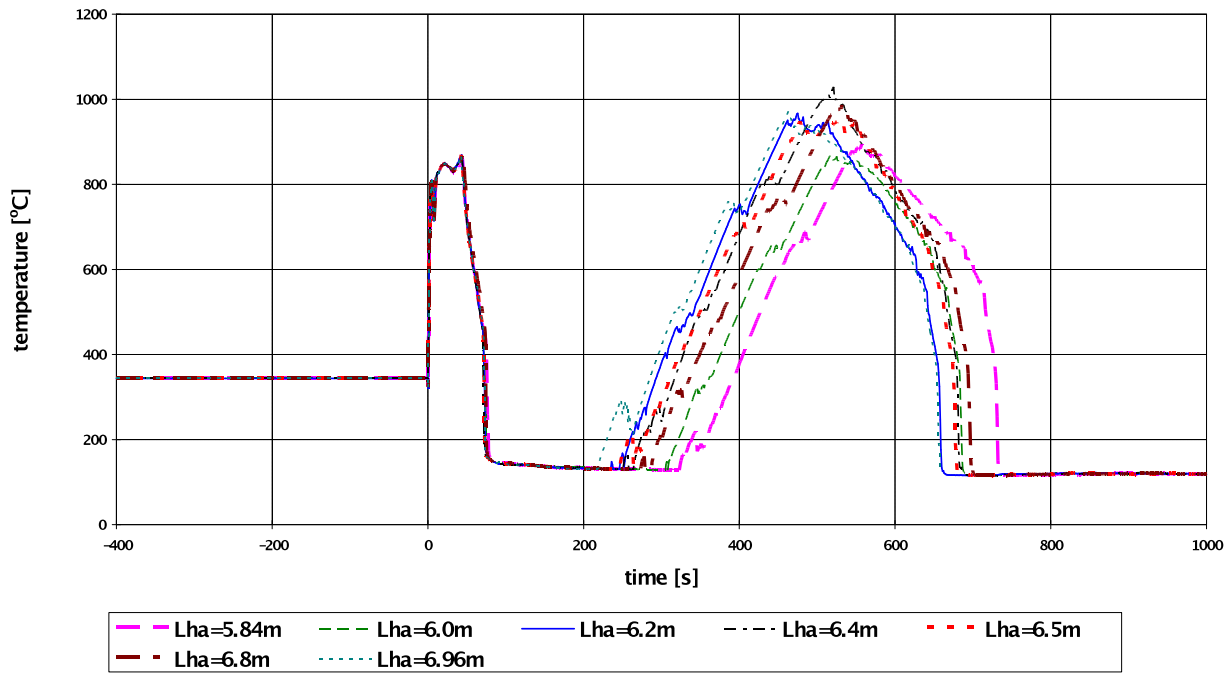


Figure 4 Maximal clad temperature in LBLOCA analyses with varying HA level

If using the deterministic approach to safety analysis, the analyst should find the worst combination of HA parameters for each LOCA or at least for the critical break sizes. In case of LBLOCA with DEGBR of cold leg, the worst combination was maximal HA pressure and maximal HA level, where the peak cladding temperature (PCT) reached 1065 °C and also the depth of cladding oxidation and amount of hydrogen were maximal. On the contrary, in case of LOCA D233 mm, the worst results were obtained with minimal HA level and minimal HA pressure. An example from sensitivity calculations on LBLOCA can be seen in Fig.4 above.

In the Figures 5 and 6, the results from the final safety analysis of LBLOCA are shown. In the Figure 5 with reactor mixture and collapsed levels, one can see a “phase with 2 levels” in the inner reactor, caused by the strong core voidage and liquid holdup in UP in the initial phase of LBLOCA. Another way of graphical interpretation of LOCA analysis results is the animation in SNAP – see Figure 7.

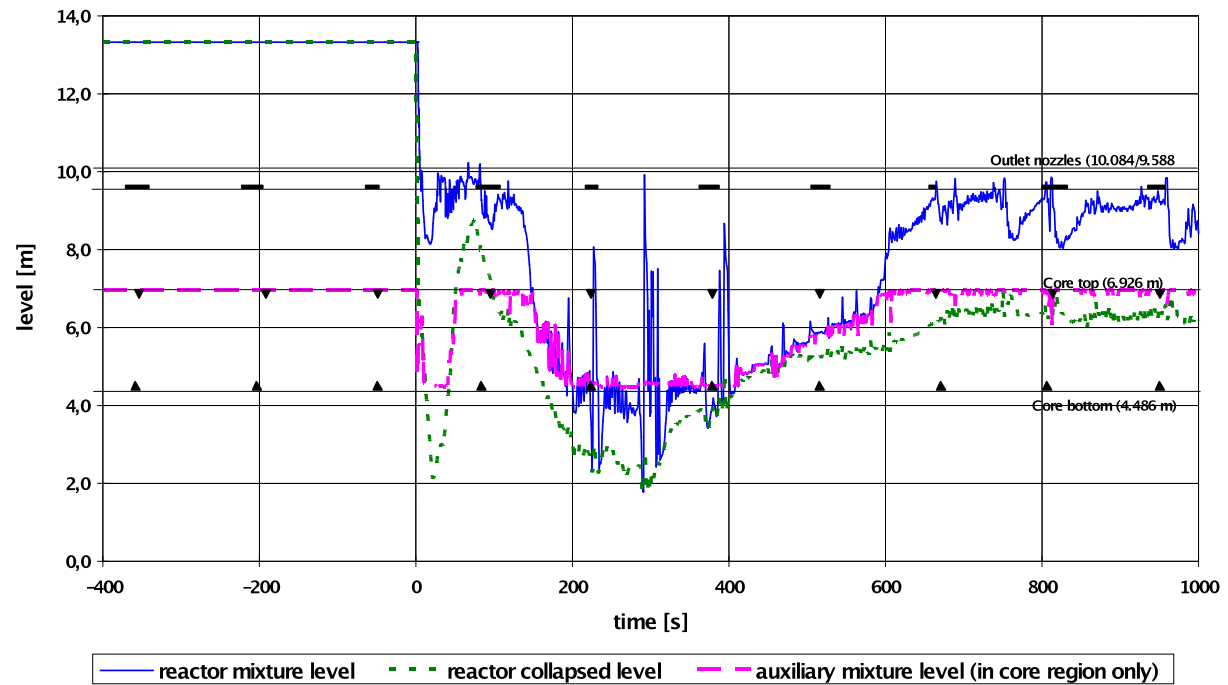


Figure 5 Reactor levels in final safety analysis of LBLOCA

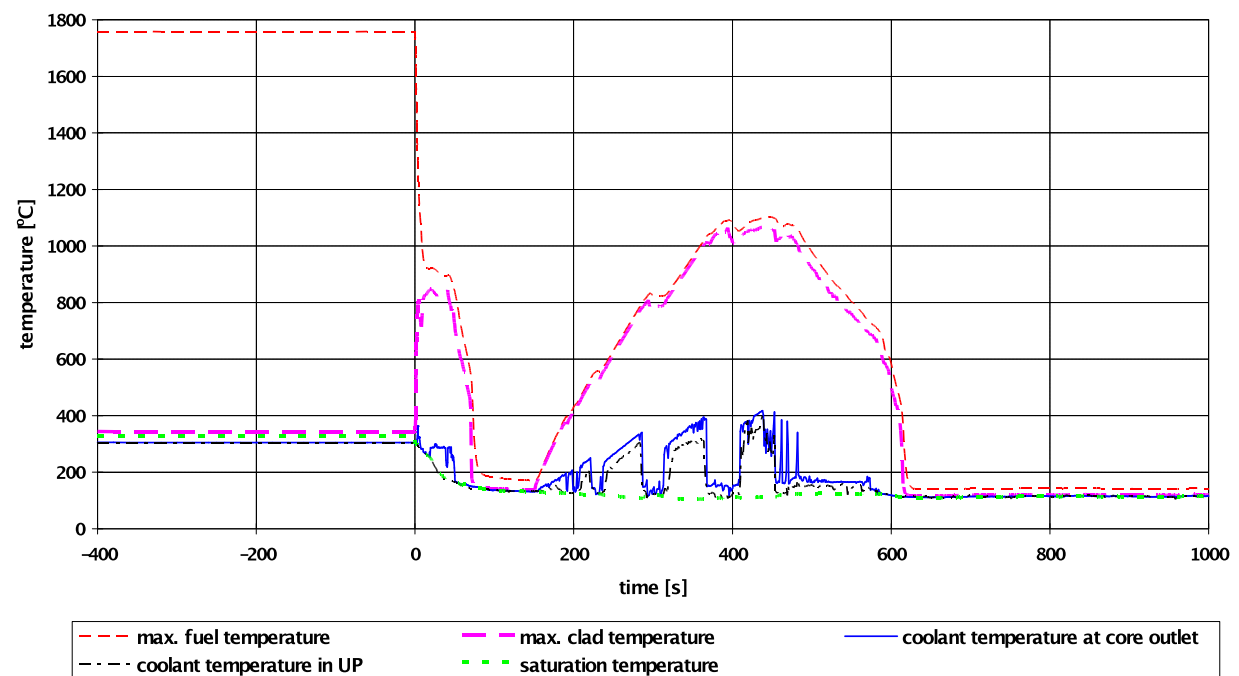


Figure 6 Core temperatures in final safety analysis of LBLOCA

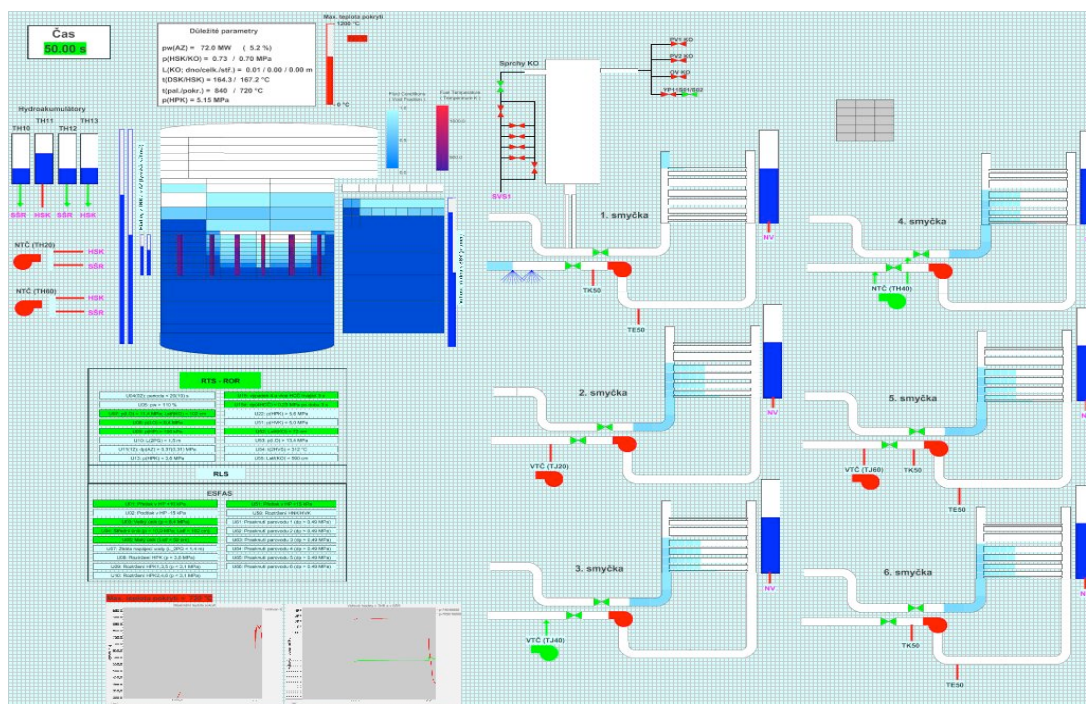


Figure 7 Animation of results from LBLOCA analysis (time 50 s, phase with HA injection)

9. Conclusion

The paper describes optimization of hydroaccumulator parameters for NPP Dukovany with VVER-440/213. The major change is the HA pressure reduction from original 6.0 MPa to 3.5 MPa, which was applied at NPP Dukovany already in 1998. Additional changes of HA parameters has been proposed lastly: the increase of HA level and the extension of allowed range of HA pressure and level. All these design modifications are based on numerous TH analyses with advanced system TH codes like RELAP5 and others. Also experimental data from VVER-design ITF are utilized. Similar design modifications were later prepared and applied at some other VVER-440's in Finland, Hungary and Slovakia.

10. References

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