ANALYTICAL SIMULATION OF IN-VESSEL RETENTION STRATEGY FOR VVER-1000/320 REACTOR USING MELCOR CODE

J. Duspiva
ÚJV Řež, a. s.
Hlavní 130, 25068 Husinec-Řež, Czech Republic
jiri.duspiva@ujv.cz

ABSTRACT

The ÚJV Řež, a. s. initiated benchmark on the analytical investigation of possibility to apply the In-Vessel Retention strategy to the VVER-1000/320 type of reactor. The benchmark was coordinated by the JRC Petten, Institute of Energy with participation of many European institutes. The ÚJV Řež, a. s. contributed to the benchmark on the IVR strategy with the integral calculation using the MELCOR code. The term “integral calculation” means that the analysis of the plant response on the events and measures applied is calculated using the one complex input model, which describes the whole unit - core, RPV, primary and secondary circuits, containment, and systems they are used during the accident progression and mitigation. Integral approach to the analyses enabled to calculated feed-back of the reactor pressure vessel cooling on the corium/debris temperature distribution and heat flux profile, regardless that the heat flux profile is strongly determined with the nodalization of the lower head wall.

The main objective of the calculation with MELCOR code is in the evaluation of accident progression and a determination of the data about mass, composition, temperature and decay power of corium relocated to the lower plenum, including processes of the degradation of the internals in the lower plenum.

Analyses were performed for the postulated accident scenario initiated with the LB LOCA (200 mm) with developing events of the loss of all active systems with the exception of systems for the severe accident mitigation – system primary system depressurization and reflooding of cavity and continuous water supply as the containment design of the VVER-1000/320 does not enable passive water drainage to cavity from the containment.

Analyses performed with the MELCOR 1.8.6 YV version predicted successful cooling of the reactor pressure vessel for sufficiently long period with the deflector applied in the cavity for the enhancement of the heat removal from the vessel surface and increase of the margin to the boiling crises. Maximum value of predicted heat flux density was 1.8 MW/m^2 in short time peak, the long term maximum in focusing area was about 1.4 MW/m^2. This is the first result of such analyses to be followed with updated ones including following up analyses of corium behavior using CFD tool (FLUENT) for more precise estimation of the heat flux profile and with the system code (RELAP5) for the vessel cooling evaluation.

KEYWORDS
Severe accident measure, in-vessel retention, heat flux density profile, MELCOR

1. INTRODUCTION

The ÚJV Řež contributed to the benchmark on IVR strategy for the VVER-1000/320 with the integral calculation using the MELCOR code [1] [2]. The term “integral calculation” means that the analysis of the plant response on the events and actions is calculated using the one complex input model, which describes the whole unit - core, RPV, primary and secondary circuits, containment, and systems they are used during the accident progression and mitigation – like RCS depressurization, hydrogen recombination, cavity reflooding and consequent water supply to cavity, hydroacumulators, but also reactor protection systems. The description of the input models is included in the “chapter 1”, the “chapter 2” summarizes performed calculations, and the “chapter 3” describes main results of selected calculations.

2. INPUT MODEL DESCRIPTION

As mentioned in the Introduction, the analyses were performed with the integral model, which is described in this chapter subdivided into logic parts – RPV plus core, primary and secondary circuits, containment with specific attention to cavity modeling, and remaining parts.

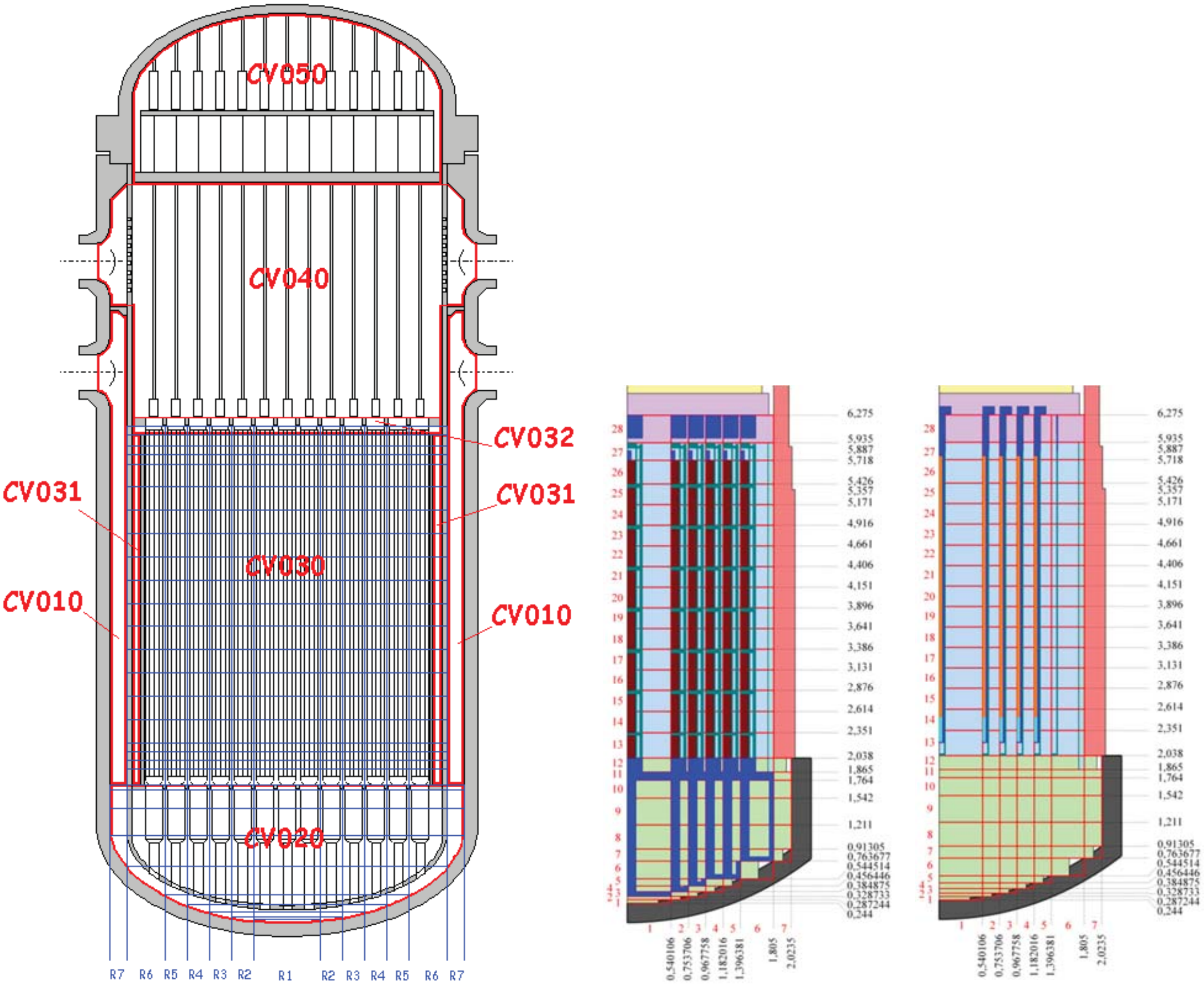


Figure 1 – Nodalization of RPV and Core – CVs and COR nodalization for MELCOR 1.8.6 [1].

2.1 RPV MODEL DESCRIPTION

The model of the RPV and core is shown at Figure 1, where the left figure shows subdivision of the RPV into thermal-hydraulics nodes (called in the MELCOR as Control Volumes – CV) with red borders and definition in the COR package, which solves behavior of intact and degraded core including behavior of corium in lower plenum. Nodalization in COR package is visualized by blue lines at left figure which is relevant for the first set of analyses (within the benchmark phases), but for the second set the center and right figures are relevant, as their difference is mainly in the simplification of modeling of core bypass, which is at left figure indicated as CV031, but this is not present at right and center ones as it was merged with CV030. Analyses with identification of differences in the core degradation prediction confirmed that such simplification is acceptable and it does not influence results in non-acceptable manner.

Model of the COR package is shown at center and right schemes of Figure 1, and these two differ in visualized components – the center scheme visualizes fuel pallets (UO2 – brown, FU component), cladding and spacer grids (Zr alloy – green, CL component), upper and lower fuel assembly nozzles (stainless steel – blue, SS component – this is mean Supporting Structure), structures in lower plenum – core support plate, columns, and lower head of core barrel (stainless steel – blue, SS component), lower head of RPV modeled in the COR package (carbon steel – grey, Segments of lower head), and CVs of different colors of background. The right scheme at Figure 1 visualize modeling of control rods using component non-supporting structure (NS), which consists of the control rod (CR) material (boron carbide, light red color), stainless steel CR cladding (grey color), and stainless steel top nozzle of clusters (blue). Background colors are identical as they represent identical CVs with the center scheme.

2.2 PRIMARY AND SECONDARY CIRCUIT AND CONTAINMENT MODELS

Model of primary and secondary circuits is based on basic assumption of number of modeled loops – loop no. 1 is modeled as independent, loops no. 2 and 3 are merged into double model loop, and loop no. 4 with connection to pressurizer via surge line is modeled as independent.

Model of containment includes all parts of hermetic rooms, but rooms below containment base-mate are not modeled in the version used for the IVR strategy simulation. Surrounding rooms to cylindrical part are merged into one CV together with rooms below base-mate. Generally containment can be subdivided into two parts – reactor hall (upper part) and lower rooms. Reactor hall is one huge space, which is in the model subdivided into 11 CVs virtually due to need of flow pattern modeling, but lower part is modeled using 19 CVs as some rooms are merged into common CV, but main parts/rooms of the containment are modeled independently – like SG boxes or cavity or recirculation sump. This nodalization is used for the integral analyses of the severe accidents, but in case of the application of the IVR strategy original CV810 (reactor cavity) is subdivided into more CVs to model the deflector expected to be installed in the cavity.

Concerning a possibility to apply the IVR strategy for the VVER-1000/320 reactor, it is necessary to mention a set of limiting conditions. The principle limitation to this strategy is that the recirculation sump of the containment is one floor below the reactor cavity, and all drainage of water inside of the containment is directed to recirculation sump. It is fully impossible to manage redirection of the water drainage to the reactor cavity, so the only external reflooding and water long term supply systems have to be added. The second limitation is in the design conditions of the cavity with very thick wall, so the only possible solution of connection of water supply is via. venting lines. Next limitation is related to the power of the reactor, which is relatively high (1000 MWe with assumptions of future power uprate in range of few percent) and heat flux density profiles and their maxima to be removed. As these values seems be very high (it has to be confirmed and the benchmark is one of activities for the confirmation), it is assumed that boiling in free water pool is not sufficient and intensification is needed. One of such possible solution is an application of the deflector.

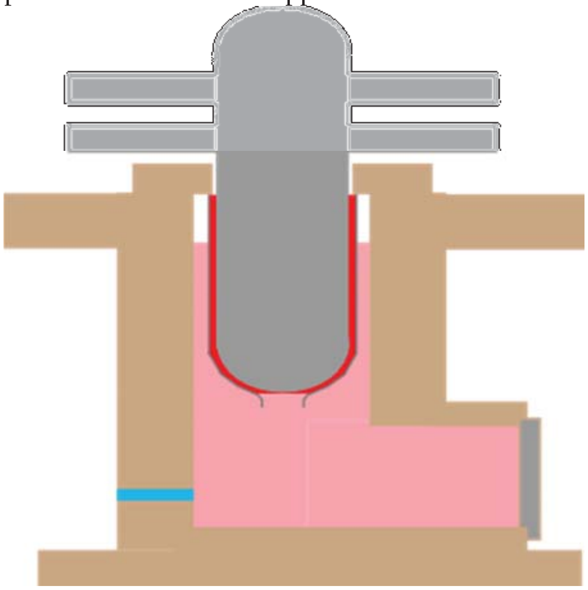


Figure 2 – Variants of deflector design in reactor cavity of the VVER-1000/320 containment (left with full height deflector and right with short deflector)

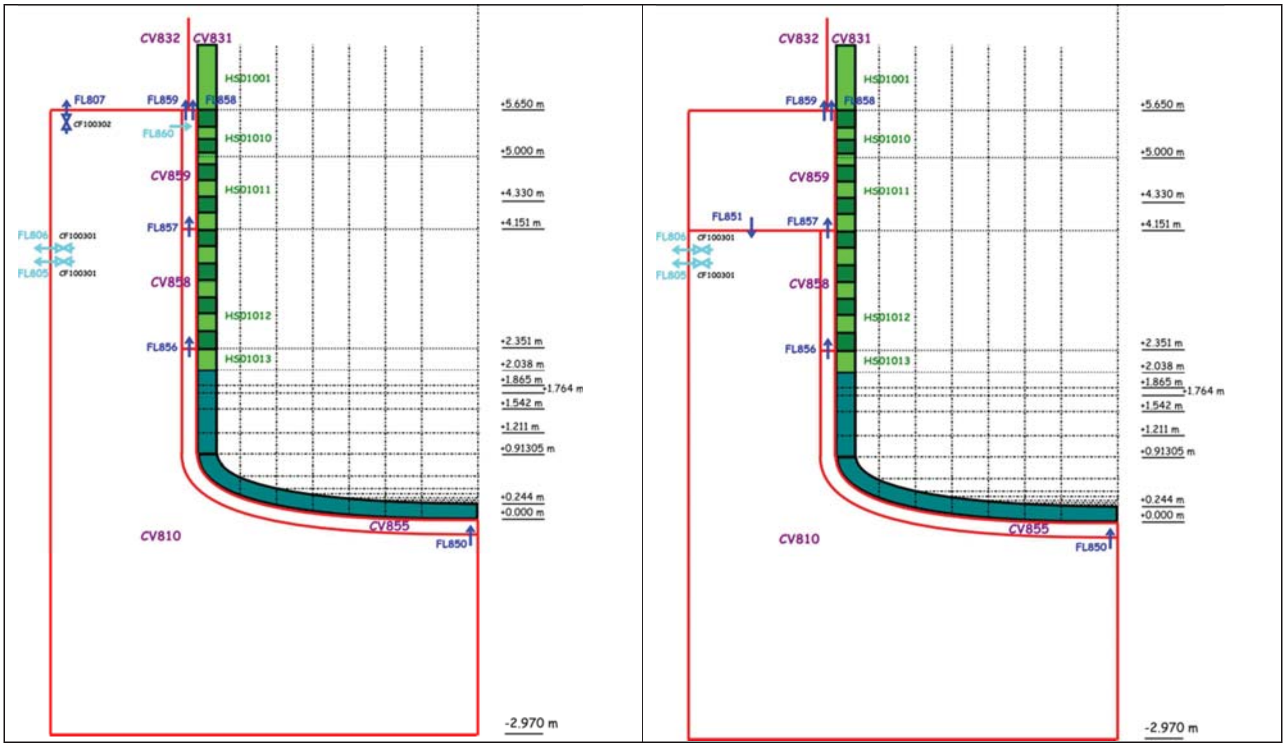


Figure 3 – Nodalization of reactor cavity of the VVER-1000/320 containment with two variants of deflector design (left (v05) with full height deflector and right (v06) with short deflector)

Figure 2 shows two design solutions of the deflector. Left part shows flow-through variant without a possibility of intensive internal water circulation inside of the reactor cavity. Right one, with short deflector, enables formation of the internal coolant circulation in the cavity, which results in the faster flow inside of the deflector and increase of the CHF profile along the RPV surface. The nodalizations of those two solutions are on Figure 3, and both variants were applied in analyses (code v0x is later used in the definition of assumptions of each of analyses performed) with the MELCOR code.

2.3 OTHER MODELS

This chapter briefly describes other important models concerning the application of the IVR strategy mainly. Generally there are many additional models included in the whole plant model starting with the reactor protection system modeling, modeling of safety systems – hydroaccumulators, LPI, HPI, containment spray systems, SG feed water system and emergency FW systems, heaters in the pressurizer, PORV and SV of the pressurizer, the membrane of the bubble tank, the steam dump to condenser and atmosphere systems, SG safety valves and others. Concerning the severe accident phenomena, the hydrogen removal system is expected, which consists of the set of PARs. Other systems related to the severe accident, which are modeled, are related to possibility of operator full opening of all pressurizer valves to fast depressurize RCS in the case of the high pressure scenario (like SBO), an activation of the cavity initial fast reflooding, and a consequent water supply to maintain a predefined water level in the cavity. Those system models are based on the source CV (time independent CV – full of water) and FL with the valve which activates (open) for initial reflooding based on a signal of the entry to the SAMG plus predefined delay (with possibility of user choice of its duration in the input file) and for the control of water level which open or close the flow path for long term water supply. Based on the amount of water added into the cavity during water supply phase, the same amount is removed from recirculation sump to prevent overfilling and overpressure of the containment.

3. CALCULATIONS PERFORMED

As mentioned in the Introduction, the analyses were performed with the integral model and two main initiating events were simulated leading into two different severe accident scenarios.

The first initiating event is LBLOCA (D_{eq} = 200 mm on cold leg between MCP and RPV) and additional events resulting into the progress into the severe accident are loss of all active ECC systems (LPI, HPI, FW, EFW, Containment Spray), the only functional systems are passive ones (hydroaccumulator, PORV or SV) and systems dedicated for severe accident management – PARs, reflooding of cavity and water supply to the cavity.

The second initiating event is station blackout (SBO), which results in loss of all active systems – from the point of modeling it means loss of LPI, HPI, FW, EFW, Containment Spray, the only functional systems are passive ones (hydroaccumulator, PORV or SV) and systems dedicated for severe accident management – PARs, depressurization of primary circuit (opening of all PORV and SV of the pressurizer), reflooding of cavity and water supply to the cavity.

Calculation of both scenarios was initiated with the full height configuration of the deflector (left figure on Figures 2 and 3) using the MELCOR 1.8.6 (release 3481, later 4073) [1]. The calculations were very unstable with many terminations due to non-convergence mainly in the COR package, but also heat structure package contributed with some terminations. Generally, terminations resulting from the HS package were possible to overstep using some repair measures in the input file, but many of the termination caused from the COR package were fatal. Regardless of those troubles, the first results were presented at the May 2014 meeting of the Benchmark. These cases were re-run, but only LBLOCA (in version v05) was successful for sufficient time to make any conclusion. But a user fault in the definition of water supply system model was identified, which caused termination of water supply after certain time.

As by product, this case is an example how the unit would behave in case of loss of water feed into cavity during fully developed molten pools within the IVR strategy application.

The case with short deflector was successfully calculated for the LBLOCA (v06 case) using the MELCOR 1.8.6 and predicted the most important results, regardless the run was again terminated due to trouble in COR package, but several thousand seconds after the full development of molten pool configuration and quasi steady simulation of the IVR strategy.

The cases of the SBO initiating events were not successful as they were usually terminated during the formation of molten pools and any reasonable results were not possible to extract. Such activity need more time and it is expected to continue in these activities in this branch.

Another activity was focused on the conversion of the input from the MELCOR 1.8.6 to version MELCOR 2.1 and running both scenarios with this latest version, which is expected as upcoming production version of the MELCOR code. All cases, they were run with many sub-released code revisions (MELCOR 2.1 rel. 4206, 5026, 6220, 6312, 6330, 6342 and also 6616 [2]) resulted in the practically identical terminations during very early phase of core degradation (during initial formation of particulate debris in center part of the core – axial level 22 of 28, but lower 12 levels represent lower plenum). Two subcases were analyzed as the original modeling with the advance B4C oxidation model was terminated due to problem in this advance B4C models, the version with the simple B4C model was always terminated at practically same time due to non-convergence in COR package (CORRN1 routine time step cutting). So the activities in the branch of MELCOR 2.1 are now temporarily frozen.

Summarizing the activities with the MELCOR code, results presented in the benchmark report come from two calculations LBLOCA_v05 (case with full height deflector and later loss of water supply into cavity) and LBLOCA_v06 (case with short deflector). This paper includes results of only case LBLOCA_v06, but also with some touches to the case v05.

4. RESULTS OF LBLOCA_V06 CASE

The chapter 3 summarized calculations and identified two main cases of the LBLOCA scenario – case v05 and case v06 with short deflector. Table 1 compares timing of main events and shows that the initial progression is in very good agreement. Differences are caused by modifications in the cooling of RPV as both simulations were done with same version of the MELCOR 1.8.6 release 4073. Concerning of both cases the formation of convective molten pool in the lower head was predicted in similar time at about 15 000 s.

As the MELCOR code is the integral code and its treatment of the IVR strategy modeling is simplified and influenced by user nodalization assumptions, the main purpose of the code is in identification of time dependence of debris/melt relocation to the lower plenum, their temperature and general behavior (passing through lower head internals), melting of remaining intact lower head internals, identification of the decay power history in the corium and indicative identification of general behavior. As addition the impact of the strategy to the containment response and estimation of external source term can be also evaluated. On other hand, it is obvious that the code can’t be used as the only tool for proving of the applicability of such strategy for the NPP, it has to be confirmed using additional and more detailed analyses of corium behavior inside of the RPV lower head and cooling outside of RPV wall including comparison with the specific CHF profile. The activities of the UJV with the MELCOR code within the benchmark were focused mainly on identification of corium composition and identification of decay power history in the debris/corium in lower plenum. Global evolution of scenario was also evaluated, but as indicative results only.

Table 1 – Comparison of timing of main events of cases LBLOCA_v05 andLBLOCA_v06.

Event	Time [s]	
	v05	v06
Initial Event Occurred	0.00	0.00
Reactor SCRAM	0.11	0.11
Hydroaccumulator YT12B01 – First Injection	153.41	153.67
Hydroaccumulator YT13B01 – Empty	291.98	297.64
Cladding rupture due to overheating	1844.12	1827.21
Core Exit T > 650° C – Entry to SAMG Signal	1988.10	1989.54
Change of FL911 Status – CAV Reflooding initiation	2168.19	2381.68
Failure of Core Support Plate – relocation to LH	5433.55	5060.00
Switching to continuous water supply to Cavity	6762.93	6710.90
Calculation terminated by: COREU3 T Convergence	14551.50	12705.00
LHF in Segment 6 by creep rupture	19265.30	-
Calculation terminated by: COREU3 T Convergence	-	21934.24

Table 2 – Final composition of material in lower plenum in case LBLOCA_v06.

Component/material	Mass [kg]
Steel total	4.5486E+04
SSOX total	1.0122E+03
UO2 total	8.5885E+04
ZR total	2.3195E+04
ZRO2 total	8.1015E+03
Total	**1.6368E+05**

Table 2 shows the final composition of materials in the lower plenum in case LBLOCA_v06 and their evolution is shown on Figure 4. Data shows that at the end of simulation the total mass of corium is 163.63 ton, the oxidic part (sum of UO2, ZrO2 and SSOX) is 95 ton and metallic materials (steel and Zr) is 68.68 ton. The ratio of Zr oxidation is 20.5 % calculated from the masses of ZrO2 and remaining Zr, recalculated to the initial mass of Zr. This ratio identifies that for the LBLOCA scenario the oxidation is not very intensive, as expected, because, due to the low pressure in the primary circuit, the content of steam in the core is also very low and such conditions are favorable for the steam starvation.

Figure 5 shows that the trends are very similar in cases v05 and v06. Figure 6 (left) shows that mass of UO2 particulate debris in the lower plenum is increasing first, but later decreases as UO2 is melted and mass of UO2 is thus converted from PD component to molten pool. Very interesting is Figure 6 (right), which presents evolution of masses of convective molten pools. It is very well visible that the mass, mainly of oxidic pool, is increasing during debris heat up/melting phase (14 000 to 17 000 s), but later, probably due to cooling of the corium in the lower head, masses of molten pool oscillate as the criteria for inclusion to the convective melt pool are fulfilled or not in some COR cells. Comparison of Figures 6 left and right shows that the modeling in the MELCOR is quite complicated, as the mass in the component “molten pool” does not means mass of convective melt pool. Moreover, the only total mass of the convective melt pools (oxidic and metallic) are available output variables, but not masses of melt pool component in each of cell, so it is not possible to create a figure of the evolution of molten materials in lower plenum as sum of all lower plenum COR cells. The only indirect way could be used to subtract mass of PD from the total mass, but it is a little user non-friendly.

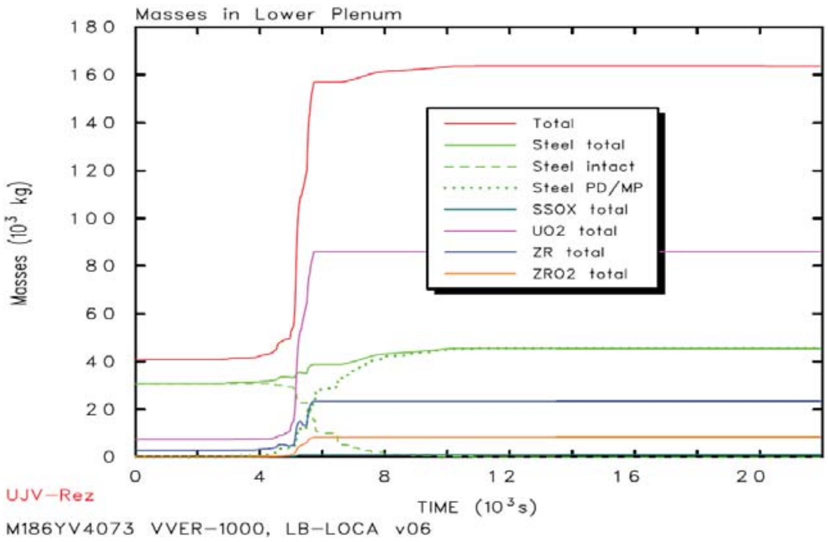


Figure 4 – Evolution of component masses in lower plenum in case LBLOCA_v06.

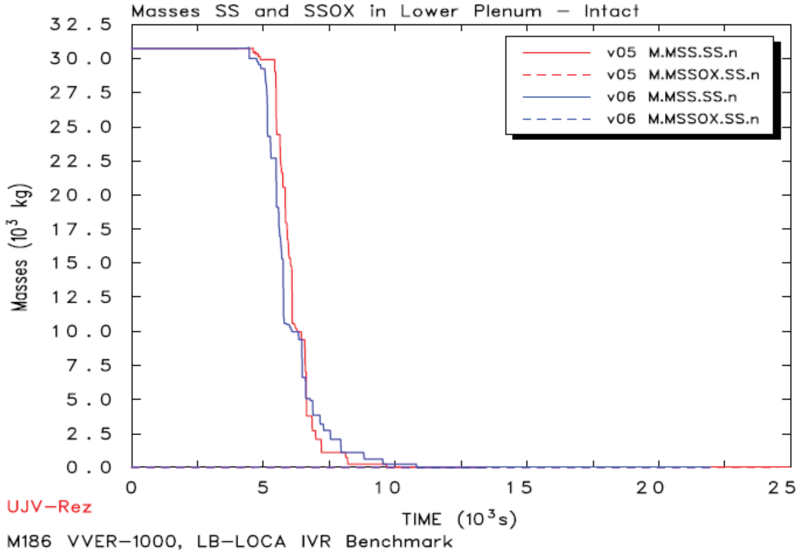


Figure 5 – Evolution of steel intact mass in lower plenum – comparison of LBLOCA cases.

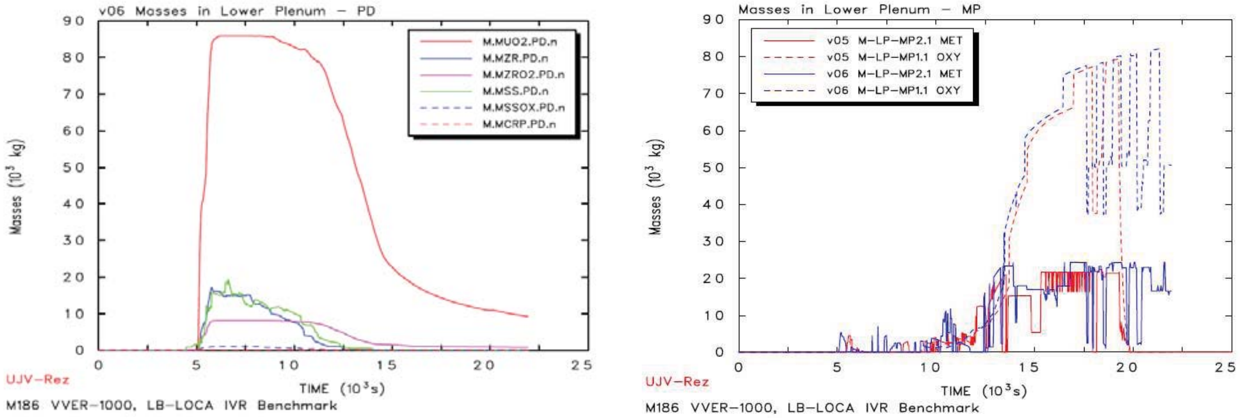


Figure 6 – Left - Evolution of PD masses in lower plenum in LBLOCA_v06; Right - Evolution of convective pool masses in lower plenum – comparison of LBLOCA cases.

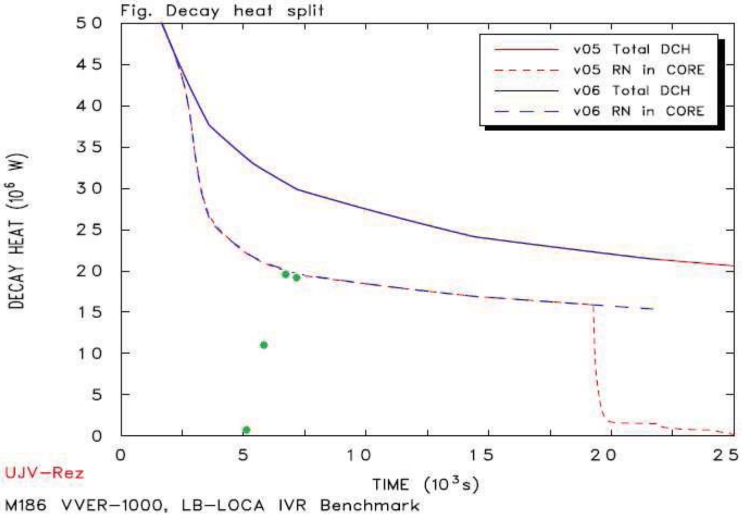
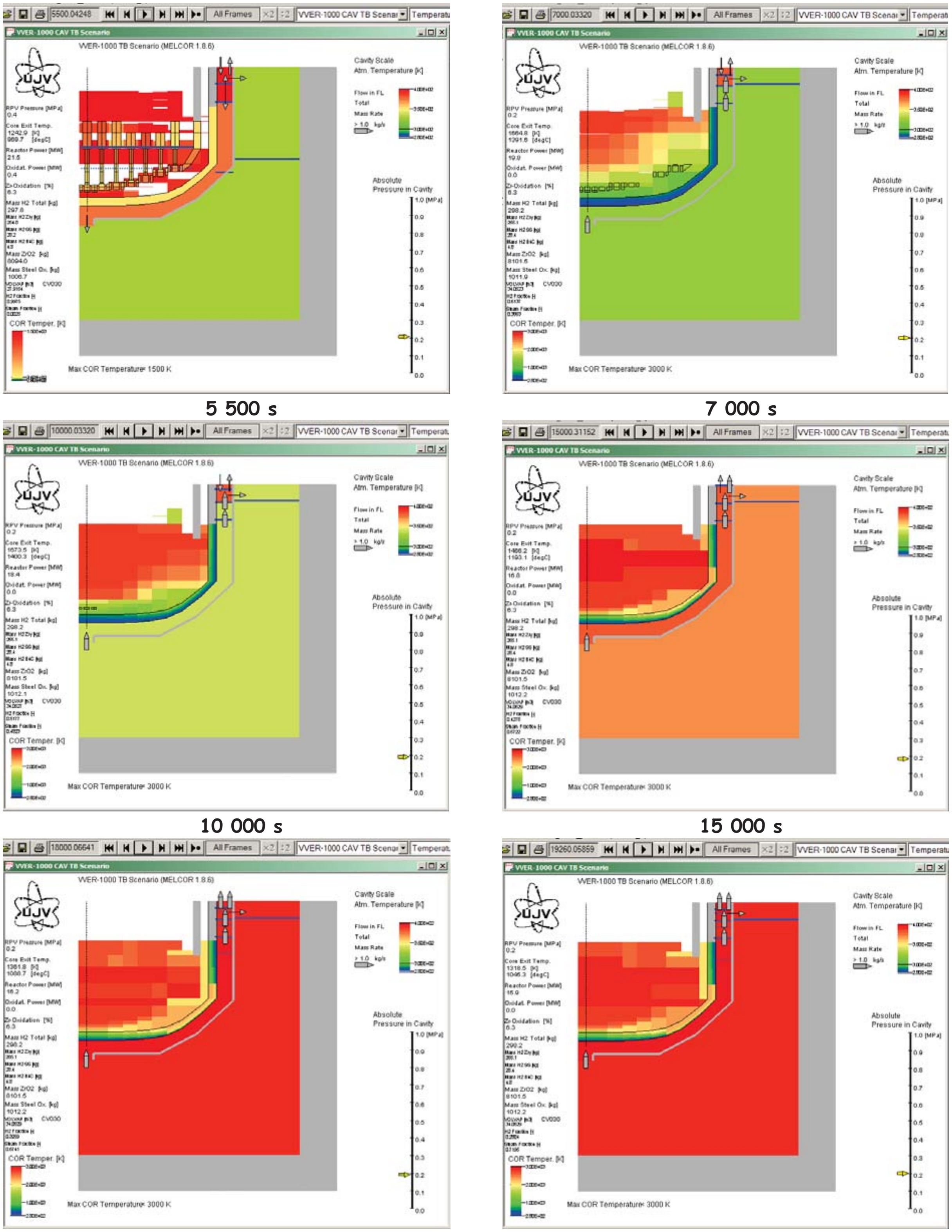


Figure 7 – Evolution of decay power distribution – comparison of LBLOCA cases v05 and v06 (green dots represents part of total decay power releasing in lower plenum in case v06 during transition period from 5000 to 7000 s)

As mentioned above, one of the important outputs from the integral analysis is evolution of decay power releasing in debris/melt in lower plenum. Figure 7 compares evolution of total decay power (solid line) and decay power releasing in core (dashed line) – it means decay power releasing in all component of core package in all cells, i.e. in core region as well as in lower plenum. To identify what is decay power in lower plenum, it is necessary to sum data per component and cell from the listing formatted output, which is available only for predefined times. This is the source of green bullets at Figure 7 and it shows that the total decay power is releasing in the lower plenum location very soon after the onset of the material relocation.

In any case, this integral simulation shows that the approach of the stand-alone simulation which assumes that total mass and total decay are available in the lower plenum immediately after the initiation of the corium relocation to the lower plenum is not fully correct and corium mass and decay power have to be treated with their histories of evolutions.



5 500 s

7 000 s

10 000 s

15 000 s

18 000 s

19 260 s

Figure 8 – Visualization of lower plenum, RPV wall and coolant behavior with ATLAS (case LBLOCA_v06)

Concerning the results of corium behavior in the lower head, set of figures was prepared using the postprocessor ATLAS (developed by GRS [3]). The screen used visualizes temperatures and presence of decries/melt (box with border line of color based on temperature color scale in lower left corner) in lower plenum COR nodes, but also intact components (boxes with black border line), temperatures of lower head segments and nodes of segment, but also temperature of atmosphere/water outside of RPV, but using different color scale table (in upper right corner) and water level as blue line (solid for swollen level and dashed for collapsed). The same screen was used for both cases v05 and v06, but it is fully representative for nodalization of cavity and deflector as in v05 case and in case v06 the behavior in upper part of cavity is not visualized absolutely correctly (compare with Figures 2 and 3), but it is possible to make some imagination of cavity response also for this v06 case.

Generally it is possible to say that the progression of accident in the lower head took a lot of time, mainly concerning the time needed for melting of remaining intact component in lower head – but it is influenced by presence of water in lower head during corium/debris relocation process, which caused significant subcooling of debris, below melting temperature of steel. Generally periphery of lower head was significantly subcooled and it was necessary to heat up it. This is a reason, why the principal heat removing to water is in case of integral analyses predicted with significant delay in comparison with stand-alone calculations.

Figure 8 shows the progression of the scenario LBLOCA case v06 in the lower plenum, bottom head wall and coolant in cavity visualized with the ATLAS tool. Only six time snapshots are shown in Figure 8, but they very well identify the most important phases of evolution. Relocation to the corium/debris at the beginning, followed with boil off of remaining water content in the lower head, formation of melt pool in the bottom head with melting of remaining internals.

The most interesting output from the analyses is the axial profile of heat flux densities. Figure 9 shows profiles for selected times and also maximum values of all times for each of levels. It is obvious that the highest values are reached at top of oxidic pool. The evolution of maximum heat flux density value predicted in the integral simulation with the MELCOR 1.8.6 integral code is influenced by some reasons.

- Relocation of corium into the lower head is “per partes” as the code predicts loss of supporting function of supporting structures they model the sore support plate, but also columns in the lower head of the core barrel. Corium relocating below core support plate enters to the inner space of upper part of columns (upper part is hollow, but lower one is solid) where is temporarily hold up, because of presence of water in lower plenum which support of cooling of the columns, freezing of corium inside, and delays the loss of column integrity and further relocations of corium.
- Due to temporarily hold up of corium and presence of remaining water, corium relocates on the bottom of the RPV as solid particles and their cooling is supported with boil off of remaining water in the lower head of the RPV, after the water boil off the corium debris are re-heat up and finally re-melted.
- Location of the maximum heat flux is influenced by the accident progression as well as the predicted part of the material already molten (metallic layer is fully molten, but oxidic part includes important contribution of solid debris – in MELCOR terminology “particulate debris”). Generally the location of the highest heat flux density is at elevation of top of oxidic pool. This is typical for cases with reduced heat transfer from the bottom oxidic melt pool to the upper metallic layer – for instance when the top crust at oxidic pool would be formed. But as the crust formation is not modeled in the MELCOR code (see COR-RM-71 page of [1]), the reason is in correlation for the heat transfer between molten pools, which depends on Rayleigh number (and the temperature difference between the bulk pool and the interface), which is in case of partly solidified oxidic pool underestimated (composition of molten material with solid particles).

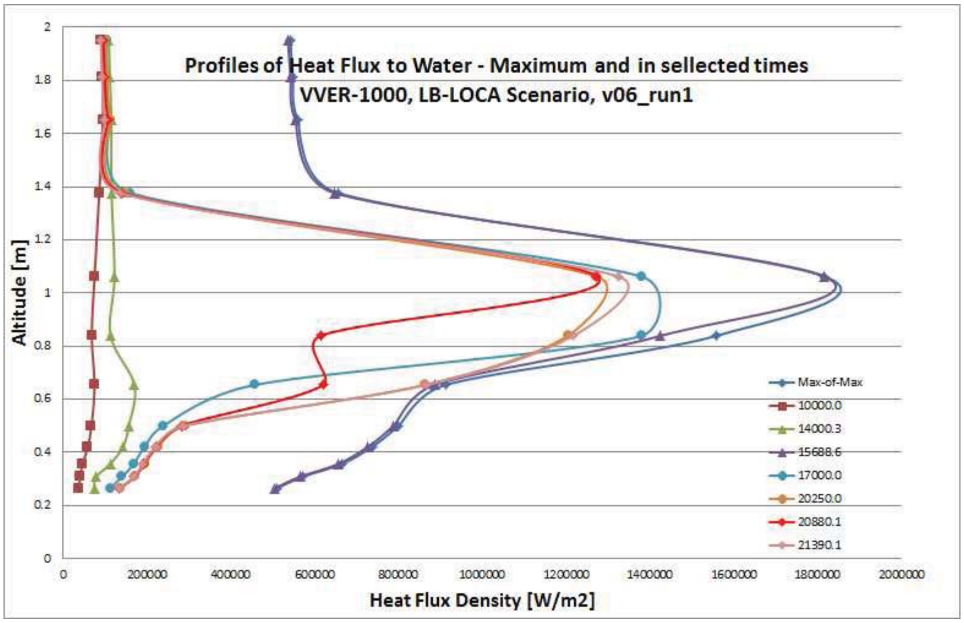


Figure 9 – Profile of heat flux densities from RPV surface to water in selected times plus selected maximal values in all times for each of location (MELCOR calculated points highlighted by bullets, curves were generated as smooth lines in Excel, so they don't represent real profile) (case LBLOCA_v06)

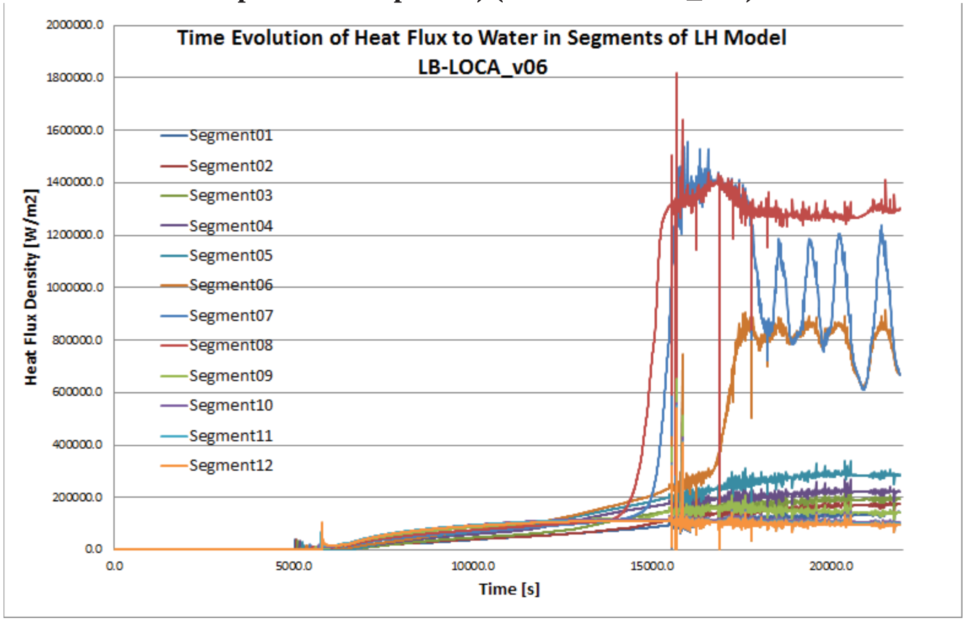


Figure 10 – Evolution of heat flux densities in segments of MELCOR 1.8.6 LBLOCA_v06 case

Not only the profile of heat flux density along the bottom head is important output, but also the evolution of the selected points (here represented by segments of the lower head model in COR package) is very interesting (Figure 10), because it shows real values of maxima, because some just only peak values has to be eliminated from the real profile, so the maximum heat flux density in the MELCOR 1.8.6 simulation of the LBLOCA in v06 case is 1.4 MW/m^2 for short time period, long term maximum is slightly below 1.3 MW/m^2, but the absolute maxima of very peak temporary value was a little above 1.8 MW/m^2.

5. CONCLUSION

The ÚJV Řež, a. s. contributed to the benchmark on IVR strategy for the VVER-1000/320 with the MELCOR 1.8.6 calculation of the LB LOCA initiated scenario. Although it was expected to submit also simulations of SBO initiated scenario and calculations preformed with the MELCOR 2.1, those case were not succeeded in passing through calculation of reasonable part of scenario, to be able to submit results. It is expected to continue in this effort in future.

The predictions of a severe accident progression with the integral model showed an importance of simulation of some phenomena which participants with stand-alone model neglected – like boil off of remaining water in lower plenum together with blockage of debris relocation to RPV bottom with the internals and their needs for heat up and melt-through. Those phenomena results in significant delay in prediction of start of intensive heat transfer through lower head into the water in reactor cavity. Although the capability of the integral code for the modeling of IVR strategy has some limitations, it is very useful tool which can produce important information needed for the definition of the stand-alone simulations. They also confirm results, including maxima of heat fluxes concerning their approximate value, but received with taking into account of many phenomena neglected or modeled in simplified manner in the stand-alone simulations.

ABBREVIATIONS

B4C	...	Boron Carbide
CHF	...	Critical Heat Flux
CL	...	Cladding, component in COR Package
COR	...	Package of MELCOR code which solves fuel behavior and its degradation
CV	...	Control Volume
DBA	...	Design Basis Accident
DCH	...	Decay heat
ECC	...	Emergency Core Cooling
EFW	...	Emergency Feed Water System
FL	...	Flow Path
FU	...	Fuel, component in COR Package
FW	...	Feed Water System
HPI	...	High Pressure Injection System
HS	...	Heat Structure
GRS	...	Gesellschraft für Anlagen- und Reaktorsicherheit mbh (Germany)
IVR	...	In-Vessel Retention
LOCA	...	Loss of Coolant Accident
LPI	...	Low Pressure Injection System
MCAP	...	MELCOR Cooperative Assesment Program
MCP	...	Main Coolant Pump
NPP	...	Nuclear Power Plant
NS	...	Non-Supporting Structure, component in COR Package
PAR	...	Passive Autocatalytic Recombiner
PD	...	Particulate Debris, component in COR Package
PORV	...	Pressure Operted Relieve Valve
RCS	...	Reactor Cooling System
RN	...	Radionuclide Package
RPV	...	Reactor Pressure Vessel
SA	...	Severe Accident

SAMG ... Severe Accident Management Guidelines
SBO ... Station Blackout
SG ... Steam Generator
SS ... Supporting Structure, component in COR Package
SSOX ... Steel Oxide
SV ... Safety Valve

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