Study of the VVER-1000 Behaviour during LBLOCA with ID 850 mm Combined with Station Blackout Using Computer Code MELCOR 2.1

P. Vryashkova, M. Andreeva, P. Groudev

Institute for Nuclear Research and Nuclear Energy, 72 Tsarigradsko shosse Blvd., 1784 Sofia, Bulgaria

Abstract. The purpose of this study is to analyse the key phenomena and processes during the transient "Station blackout (SBO) with large break loss of coolant accident (LBLOCA) with ID=850 mm". It has been analysed the processes, which show the accident progression since the beginning of LBLOCA in the cold leg to a rupture of the reactor vessel, including the total core uncovery, core heating up, hydrogen generation and fusion products release in the primary circuit after rupture of the fuel cladding, melting of the fuel and reactor core internals, and its further relocation to the bottom of the reactor vessel. For the presented analysis, it has been developing a new model for the reactor VVER-1000 with the computer code MELCOR 2.1 for severe accident. The reference nuclear power plant in this study is Kozloduy NPP, units 5 and 6. It has been compared the older version on the computer code MELCOR 1.8.5 with the new version of the code as using the same initial and boundary conditions. The difference in the development of the accident is determined mainly by differences in the models that have been recently developed and added to the MELCOR 2.1 version.

Keywords: nuclear safety, severe accident, release of hydrogen, core degradation

1 Introduction

The specific type of large LOCA is (Double Ended Cold Leg) break, which means a total guillotine type of break in cold leg pipe combined with Station blackout (SBO), is one of the most dangerous accidents in the reactor containment. To simulate the behaviour of the fuel for VVER-1000 in condition of the severe accident [1-4] is chosen the transient "Station blackout (SBO) with large break loss of coolant accident (LBLOCA) with ID=850 mm". It has been necessary to simulate station blackout of the nuclear power plant for occurring the core degradation leading to melting and relocation of fuel elements and reactor internals until the late in-vessel phase as it is simulated to work only passive safety systems. Furthermore, paper is focused on investigating the impact of some important parameters and the consequences of steam-zirconium reaction during in-vessel phase, and the consequences of significant amounts of hydrogen, which is generated in the core.

This work presents major differences and improvements of the model of the reactor VVER-1000 with MELCOR 2.1 compared to the older version, which have significant differences in accident progression.

The differences between developed model for version MELCOR 2.1 and the old model for version MELCOR 1.8.5 are hemispherical lower head geometry, models for simulating the formation of molten pools, both in the lower plenum and the upper core, crust formation, convection in molten pools, stratification of molten pools into metallic and oxide layers, and partitioning of radionuclides between stratified molten pools, reflood quench model, control rod silver release mode, new B_4C control rod oxidation model, and capability to model the VVER-100 core outer periphery. The new models in the new version of the computer code allow simulating closer to reality the physics of the processes to the bottom of the reactor vessel, thereby simulating the elliptical bottom and thermophysical processes that occur therein.

Some of the models used at the calculations are:

Changes in COR and Lower Head Nodalization Lowerhead modelling in the MELCOR COR package has been substantially modified in MELCOR 2.1, and its application has been extended to include the portion of the cylindrical reactor vessel that is the lower plate in a VVER. This replaces the previous use of the HS package to provide a radial boundary condition for that portion of the core model that is below the bottom of the core barrel. The new model also allows representation of a curved lower head. The noncylindrical portion can be a hemisphere with the same radius as the cylindrical portion of the reactor vessel, a lesser portion of a sphere of greater radius, or a flat disk. The thickness of the lower head may differ from that of the cylindrical vessel, and the transition may take place at the radius of the cylindrical vessel.

Model of material relocation The core materials can be relocated by melting and candling. They can also fail mechanically and to be converted to particulate debris, which then can slump to lower parts of the core, if there is space available. Materials interactions (formation of eutectics) are frequently involved in these processes. When materials that form core components melt, they are usually assumed to candle immediately. The exception is molten metal (zirconium and stainless steel) held up behind oxide shells.

Model of the core degradation It has been updated in the new version. Firstly, molten intact materials are moved from intact components to the conglomerate debris associated with the components. Then, if the materials interaction model has been activated, eutectic reactions are calculated between various intact solid materials within a component. If the component temperature exceeds the eutectic points, dissolution reactions between certain intact solid materials and molten eutectic mixtures are calculated (e.g., intact UO_2 fuel dissolved by Zircaloy-bearing mixtures); these materials are also added to the conglomerate debris. Molten materials are relocated downward by the candling model (provided there is no flow blockage) and radially by the spreading model, if there is a significant difference in the liquid levels in adjacent core rings. Intact components are converted to debris, if various debris formation criteria are met.

2 Description of MELCOR VVER-1000 Input Model

MELCOR 2.1 computer code [5] has been used to simulate the transient for VVER-1000/V320 NPP model compare with old version MELCOR 1.8.5 [6,7]. The new model of computer code MELCOR 2.1 has been developed at INRNE-BAS for VVER-1000/V320 Kozloduy Nuclear Power Plant Unit 5, 6 for analyses of operational occurrences, abnormal events, design basis scenarios and severe accidents, which have been developed on the base of the older model and have been extended. The model provides a significant analytical capability for the specialists working in the field of NPP safety.

In the MELCOR 2.1 model for VVER-1000/V320 NPP are included reactor vessel; core region represented by four radial rings; pressurizer system, including heaters, spray and relief valves; safety system, including high-pressure pumps, four accumulators and low-pressure injection pumps.

In the model, also is presented a make up/drain system, including connection (control) with pressurizer. Secondary side is developed too and it is presented by eight steam generators (SG) safety valves, four BRU-A valves, BRU-K valves, steam pipelines (including main steam header) and turbine including regulating valve in front of the turbine. The horizontal steam generator (SG) is modelled. Main cooling pump (MCP) is developed using homologous curves of real pumps.

The reactor and pressurizer in MELCOR 2.1 model are shown schematically in Figure 1. The radial reactor core zone modelling in MELCOR 2.1 is presented in Figure 2.

In the VVER-1000 input model, the primary system is modelled using four coolant loops, each one including one MCP and a horizontal SG. The thermal-hydraulic model configuration provides a detailed representation of the primary, secondary, and safety systems. The reactor ves-

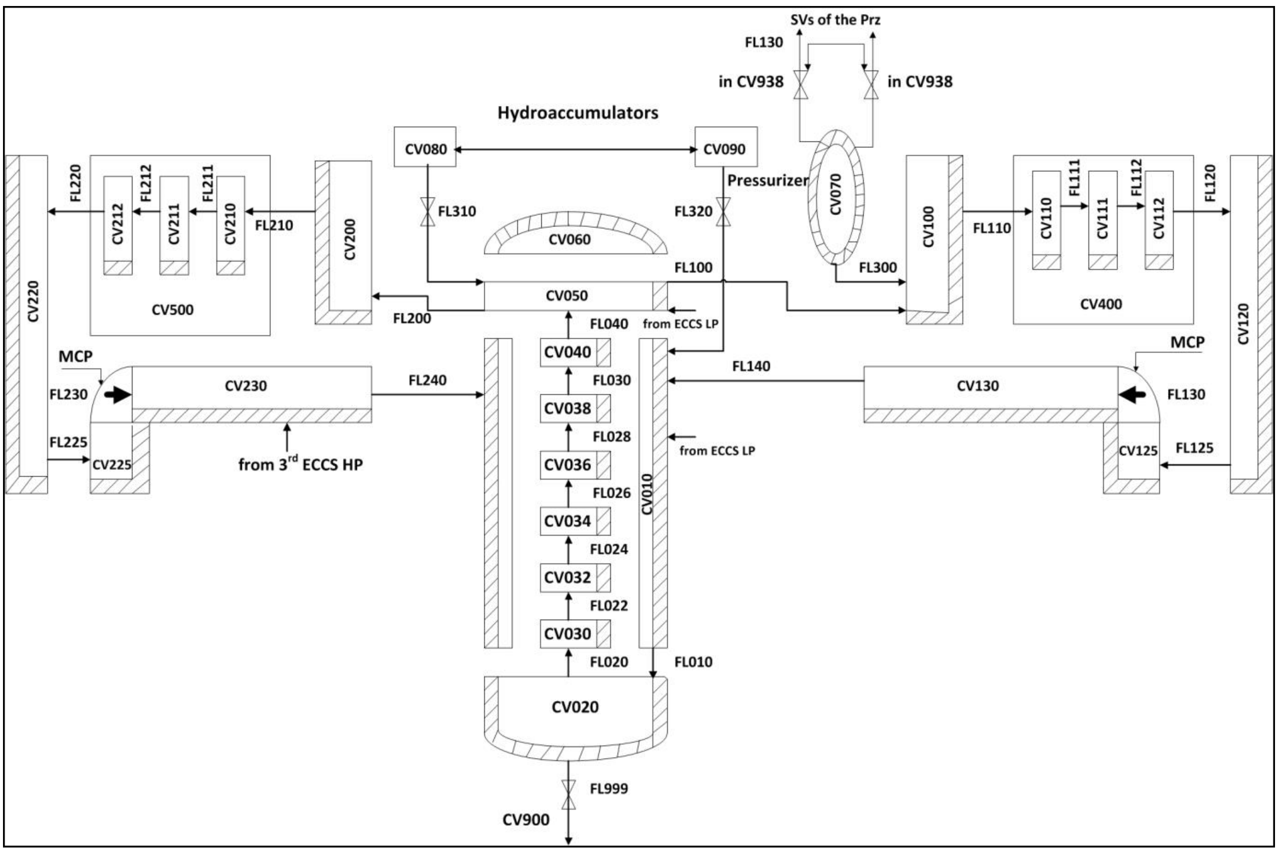

Figure 1. MELCOR 2.1 VVER-1000 primary side nodalization scheme.

sel model includes a downcomer, lower plenum and outlet plenum.

The reactor is modelled by ten control volumes. The pressurizer (PRZ) system includes heaters, spray, and pressurizer relief capability. The safety system representation includes accumulators, which are represented by two volumes; high and low pressure injection systems (Figure 1).

The core region is divided radial into 4 rings and ten axial segments, which represent the total number of fuel assemblies. The first ring represents 37 fuel assemblies and 13 fuel assemblies containing control rods, the second ring represents 54 fuel assemblies, 30 of which are assemblies with control rods, the third ring represents 72 external fuel assemblies and 18 fuel assemblies containing control rods, the fourth ring consists reactor core support barrel and core baffle (see Figure 2). The major input requirements for these components are the geometrical parameters (pellet radius, inner and outer cladding radius, plenum length and void volume), MELCOR hydraulic volumes that provide boundary conditions, material specifications, radial nodalization, initial conditions.

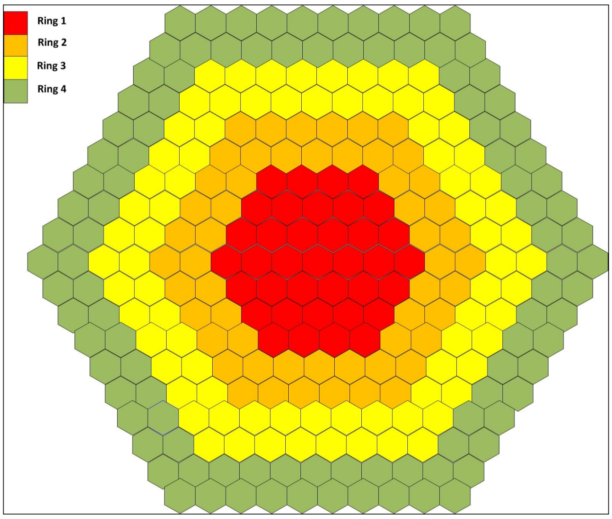

Figure 2. MELCOR 2.1. Reactor core zone modelling.

3 Description of the Scenario for LBLOCA with ID 850 mm Combined with Station Blackout

1. Initiating events:

- At the beginning time (0.0 s) from the occurrence the accident starts the Guillotine cold leg rupture (ID 850mm) between MCP and reactor nozzle;
- The all active safety systems are failing because of loss of all AC and DC power sources.

2. Investigated scenario:

— Start the instantaneous Guillotine rupture coolant pipe [RCP] in 0.0 s;

— Actuation of the reactor protection system (RPS);

— All four MCPs are switching off (due to SBO);

— The pressurizer heaters switch off;

— The make up/letdown system stops;

— Switch off the feedwater to SG (due to SBO);

— The turbine stop valves (TSVs) are closed with delay10 sec., due to the electrical protection actuation (condenser vacuum loss) and in this way the turbine is isolated;

— All active safety systems are not available due to SBO;

— All four hydroaccumulators will start to cooldown the reactor core, when the pressure drops to 5.88 MPa;

— Isolating of hydroaccumulators at low levels ($<$ 1200 mm);

— Beginning of core uncovery and heat up of the core;

— Beginning of hydrogen generation;

— First cladding creeps rupture and start of the fission products release from fuel pellets;

— Beginning the reactor core damage and slump of corium in lower plenum;

— Lower head vessel failure;

— Beginning of the slump of the corium from reactor vessel in the reactor cavity.

4 Analysis of the Results

The calculations show the comparison between the MELCOR 2.1 and MELCOR 1.8.5. The calculations have presented consequences from flow of the coolant to beginning of the slump of the corium from reactor vessel in the reactor cavity. The transient is a Station blackout with LBLOCA in 0 sec. The primary pressure drops sharply due to large inventory loss in RCS and the level in the pressurizer sharply decreases. When the hydroaccumulators are started, the pressure drops down because of rapidly cooldown on the second and primary circuit. The core uncovery depends on the RCS inventory depletion rate (governed by break area) and the rate of hydroaccumulators injection. In the event of complete loss of reactor coolant system, the reactor core would heat up due to decay heat from the core. A steam-zirconium reaction, accompanied by hydrogen release and generation of additional heat inside the fuel element cladding, begins on the surface of the heated zirconium claddings of the fuel elements.

Chronology of the main event is presented in Table 1. The results of the calculations are presented in Figures 3–8.

The primary pressure is presented in Figure 3. As a result of leakage through guillotine rupture, primary pressure decreases sharply in the 3 s of the accident under the pressure of the steam generators for both calculations. The place of Guillotine cold leg rupture (ID 850mm) between MCP and reactor nozzle is selected for the maximum possible coolant leakage.

As a result of the accident, decay heat generated in the core is provided by the leakage of coolant through double-ended guillotine rupture and work of hydroaccumulators.

Table 1. Chronology of the main events

Events	MELCOR 1.8.5 time (s)	MELCOR 2.1 time (s)
Guillotine cold leg rupture (ID 850mm) between MCP and reactor nozzle combined with loss of all AC and DC power sources	0.0	0.0
The make up/letdown system stops	0.0	0.0
All four MCPs are switching off (due to SBO)	0.0	0.0
The pressurizer heaters switch off	0.0	0.0
Actuation of the reactor protection system (RPS) due to “Three of four MCPs switched off” and after this signal all control rods drop in 2-4 s to the bottom of the core	1.6	1.6
Start of hydroaccumulators injection	3.0	5.0
Turbine is isolated	11.6	11.6
Beginning of hydrogen generation	22	22
Pressurizer water level became 0 m	27.0	24.0
End of hydroaccumulators injection	60.0	58.0
Beginning core uncovery (up 90%) – collapsed level	147	140
Beginning the reactor core damage	3394	2115
First slump of corium in lower plenum	9872	7719
Beginning of total core uncovery (collapsed level)	4156	4156
Lower head vessel failure and beginning of the slump of the corium from reactor vessel in the reactor cavity	12605	9531
End of the calculation	15000	15000

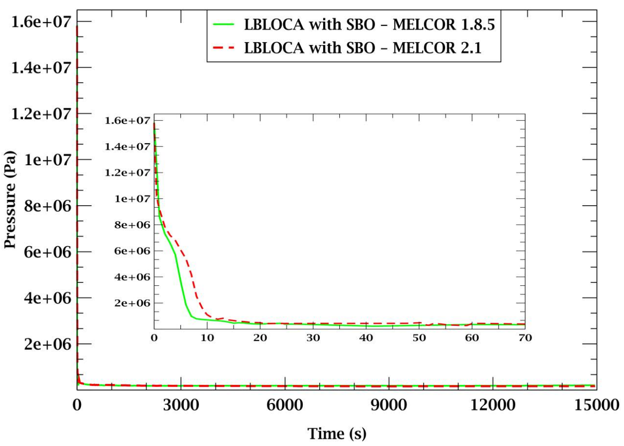

Figure 3. Primary circuit pressure.

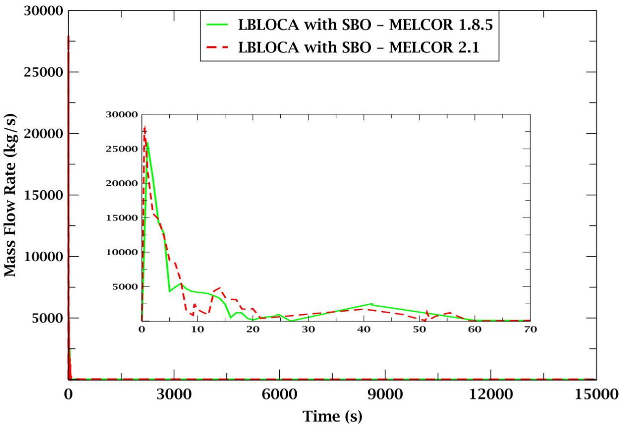

Figure 4. Mass flow rate through the leakage.

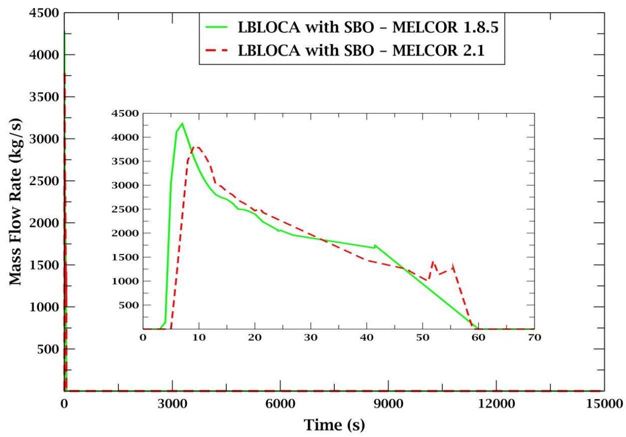

Figure 5. Injection of coolant from hydroaccumulators.

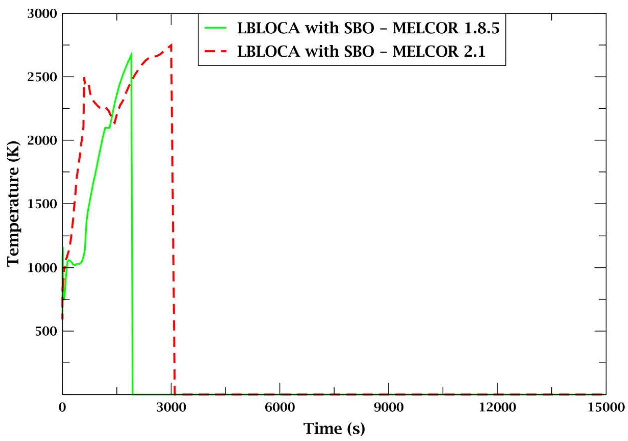

Figure 6. Temperature of the fuel cladding of the central region of the core.

At the time, when the pressure on the primary circuit decreased significantly, mainly due to the loss of coolant through the break, the primary coolant starts to boil and the core level is further reduced. Because of this reason the cold leg of the broken loop becomes empty and the break flow switches from two-phase flow to single phase vapour flow, the coolant that remains at the core starts to flash. The flow rate of the coolant is mainly dependent on the pressure in the primary circuit and from flashing through the rupture, which is shown in Figure 4.

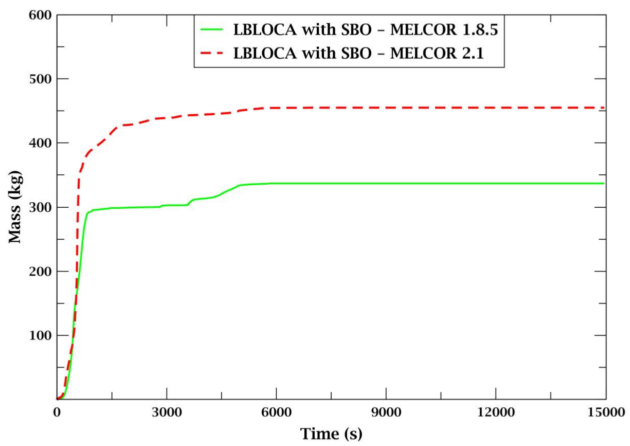

Figure 7. Mass of the generated hydrogen.

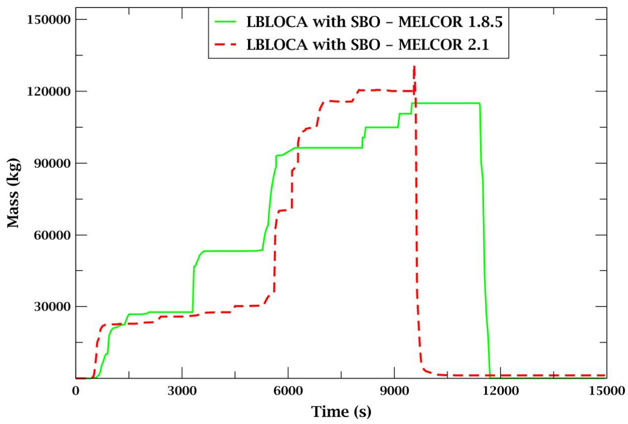

Figure 8. Mass of the corium of the bottom lower head vessel.

The primary pressure drops down sharply, and then reaches the point to start of hydroaccumulators injection in 3 sec. from the beginning of the accident for MELCOR 1.8.5 and in the 5 sec. for MELCOR 2.1 (see Figure 5).

The difference in the two versions is explained that the work of the hydroaccumulators depends on the pressure in the primary circuit, but the primary pressure also depends on the leakage through the rupture.

The next important parameter is the temperature of the fuel cladding of the central region of the core is presented in Figure 6.

An increase in the cladding temperature occurs as the fuel rods become uncovered. The fuel rods start to melt and pass into the lower levels of the reactor vessel. The progression of the temperature of the fuel cladding varies in time and height of the core for the two calculations. Differences, which are observed, are the time of the melting of the elements of the core and relocation downward of pieces into the lower levels of the reactor vessel, and slightly higher temperature of the fuel cladding for MELCOR 2.1.

The fast activation of the hydroaccumulators did not allow in the first seconds of the accident to occur steam-zirconium reaction, but the lack of systems for control residual heat removal from the reactor core in the first minutes of the accident leading to full uncovery of the core.

The rapid depletion of coolant in the reactor core leads to core heating up and upon reaching conditions for the steam-zirconium reaction, in the result of that reach the maximum generation of hydrogen in 5740 s for MELCOR 1.8.5 about 336 kg (see Figure 7) and in 5685 sec. for MELCOR 2.1 – 454 kg.

The difference in the quantity of generating hydrogen can be explained by the different parametric models, which are used in MELCOR 2.1 for oxidation of Zircaloy.

Figure 8 is presenting the total mass of the corium at the bottom of the reactor vessel.

Due to the rapid decrease of the mass of coolant in version MELCOR 2.1 compared with version MELCOR 1.8.5, it occurs much more rapidly heat up of the structure of the bottom of the reactor vessel and subsequent to its failure. For this reason, it is observed earlier failure of lower head vessel for MELCOR 2.1 in 9531 sec. and beginning of the slump of the corium from reactor vessel in the reactor cavity, while version MELCOR 1.8.5 has less corium mass and significant later failure of lower head vessel (12605 s).

The difference obtained in the results, can be explained by the use of new features to simulate the bottom of the reactor vessel and new models in the version MELCOR 2.1, which are used in the analysis.

5 Conclusion

The selected scenario allows simulating the core degradation as well as the operation of the passive safety system – the hydroaccumulators. As a result of the analysis, it is found that the model simulates the progression of the accident correctly, at the expected limit of the behaviour of processes.

In the present analysis is assessed also the generation of hydrogen during in-vessel phase.

Analysis of the melting of the core and the relocation of the debris melt at the bottom of the reactor vessel for both versions shows that the new version predicted earlier failure of the bottom of reactor vessel. The reason can be explained by earlier significant relocation of debris melt at the bottom after 6000 sec. using a new version of MELCOR 2.1. Differences in the results of some of the processes show necessary to continue the studying the processes of degradation of the core.

The performed analysis with the new developed model of reactor VVER-1000 for MELCOR 2.1 and received results gives basis to assume that the model can be successfully used for analysis of various emergency situations for NPP, unit 5 and 6 in conditions of severe accident.

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