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Assessment of VVER 1000 SAMG Efficiency During LB LOCA Accident Along With SBO Using ASTEC Computer Code

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ABSTRACT

This paper presents an investigation of VVER 1000 severe accident management guidelines efficiency during "large break loss of coolant accident" simultaneously with station blackout (SBO).

The main purpose of this assessment has been focused on the investigation of the efficiency of a second possible entrance at severe accident management guidance (SAMG) strategy (based on Kozloduy nuclear power plant (KNPP)) in case of failure of the first one and an assessment of the possibility to protect the reactor core from significant degradation and the reactor vessel failure. The other goal is the assessment of main plant parameters behavior, like: core uncovery, core heat up, oxidation of core materials, hydrogen generation, core degradation, fuel cladding failure, partial melting of the core materials with the formation of a molten pool in the reactor core, relocation of core materials to the bottom of the reactor vessel, and formation a molten pool containing corium. The scenario included a hot core quenching and recovery of a water level in the reactor core.

In the performed work a simulation of operator action, based on a SAMG at VVER 1000 of KNPP is investigated. The selected scenario is a large break loss of coolant accident (LB LOCA) simultaneously with an SBO. The accident starts with a rupture in the cold leg (with inside diameter (ID) 850 mm simultaneously with SBO). All hydro accumulators (HAs) had been available during the accident and prevent earlier damaging of the reactor core. The active safety systems are failing because of loss of all AC and DC power sources. In the selected scenario an operator action based on a SAMG is assumed: quenching of the heated core by an injection of borated water in the reactor vessel when the core exit temperature reaches 980 ºC by one high pressure injection pump (HPP) and one low pressure injection pump LPP. It is assumed that the first possible entrance into SAMGs at 650 ºC (923 K) is omitted.

The results obtained in this paper could be used for the improvement of SAMG as well as for level 2 probabilistic safety analyses (PSA).

1 INTRODUCTION

Two calculations of LBLOCA scenario along with SBO have been performed with ASTEC V2.2b computer code. A base case calculation without operator actions (using only the passive safety system HAs) - as case#1 and operator actions – as case#2, where the operator actuates one HPP and one LPP to inject in the reactor coolant system (RCS). The HPP injects only in the cold leg, while LPP injects in both: hot and cold legs after the fuel cladding temperature at the upper part of the reactor core reaches 980 °C (1253 K) [1]. The analysis discusses the importance of exact point of core exit temperature measures. Case#1 demonstrates a simulation of core degradation progression which covers in-vessel and beginning of ex-vessel phases, including vessel failure and cavity activation. Case#2 demonstrates the effectiveness of severe accident management strategy for significant core degradation prevention.

The performed LB LOCA calculation with operator action shows partial degradation of reactor core, when is missed first entrance to SAMG [2].

The investigation has been performed with severe accident computer code ASTEC. The activated ASTEC modules of the VVER-1000 input deck are: CESAR, ICARE, SOPHAEROS, RUPUICUV, CORIUM, MEDICIS, DOSE and CPA. All ASTEC modules have been used in a "coupled mode". The referenced nuclear power plant considered in this investigation is a VVER-1000 reactor of Kozloduy NPP.

2 EVENT DESCRIPTION

The event starts with simulation of a cold leg rupture (ID 850 mm) simultaneously with a station blackout (SBO).

Base case (BC) (case #1):

1. Actuation of the reactor protection system (RPS) after 1.6 s due to ''Three of Four Main coolant pump (MCP)s switched off and the reactor power is above 75%. After this signal all control rods drop in 2-4 s to the bottom of the core;
2. Due to primary pressure drop the subcooling reaches ΔT_S<10º C (activation of safety systems);
3. The pressurizer heaters switch off due to SBO in 0.0 s due to SBO;
4. The main isolating valve (MIV) closes in 2.0 s due to electrical protection actuation (condenser vacuum loss) and in this way the turbine is isolated;
5. The turbine bypass valves (TBV) are not available (all four BRU-K – dump to the condenser) due to loss of condenser vacuum (due to SBO);
6. The feed water pumps switch off at 5.0 s. The emergency feed water pump (EFWP) switches off due to SBO;
7. The make-up system stops at 0.0 s due to SBO (the draining line is closed).
8. All active safety system has failed due to SBO.
9. The auxiliary feed water pumps switch off.
10. All four HAs (Passive Emergency Core Cooling System - YT) will start to cooldown the reactor core when the pressure drops to 5.88 MPa (60 kgf/cm^2).

Operator actions (OA) (case#2):

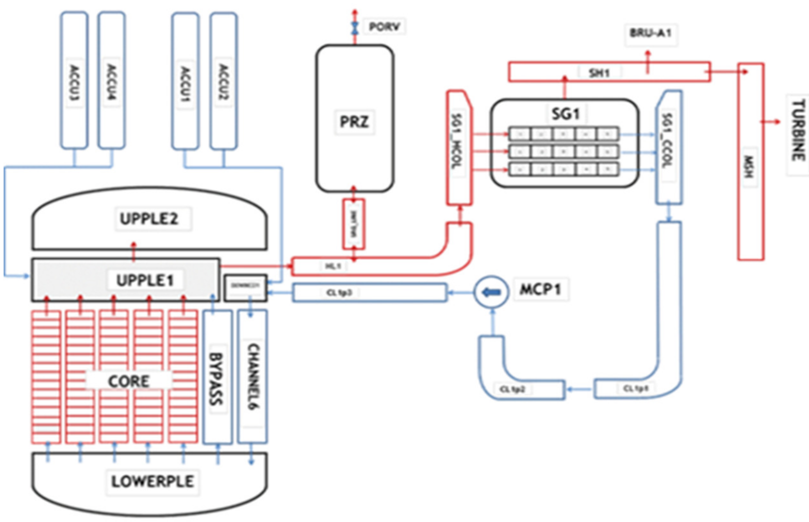
11. Activation of Diesel generator (DG) after reaching 980 ºC (1253 K) of core exit temperature.
12. Entrance in SAMG after reaching 980 ºC (1253 K) temperature at core exit (assuming missing of the first entrance at 650 ºC (923 K)).
13. When the RCS pressure falls below 10.78 MPa (110 kgf/ cm^2), the one HPP begin to inject borated water in the cold legs. At that time pressure is very low.
14. The one LPP will start to inject borated water after reaching set point of injection – 2.54 MPa (26 kgf/cm^2). At that time pressure is very low.

3 ASTEC INPUT MODEL MAIN CHARACTERISTICS

In the ASTEC V2.2b [3] input deck for VVER-1000 the following modules have been activated: CESAR, ICARE, SOPHAEROS, RUPUICUV, CORIUM, MEDICIS, DOSE and CPA. The nodalization scheme of ASTEC input model - Reactor vessel and primary circuit is presented on Figure 1.

All ASTEC modules activated in a "coupled mode".

Figure 1: Nodalization scheme of ASTEC input model - Reactor vessel and primary circuit



The reactor vessel structures are modelled with ICARE module, which includes reactor core, baffle, the cylindrical part of the barrel, vessel cylindrical part, fuel assembly supports and vessel lower head. The primary side: four loops have been modelled in two ASTEC loops - one single loop and the other 3 loops lumped in a common loop. Each one of the ASTEC primary loops is modelled by 7 volumes and 8 junctions representing the hot leg, steam generator (SG) hot collector, SG tubes, SG cold collector, cold leg (presented by three parts) and an MCP. The pressurizer with 3 relief valves and surge line has also been modelled.

The reactor core is divided in axial and radial direction (twenty nodes in axial direction and five rings in radial direction, including baffle and barrel). Upper plenum has been modelled by two volumes: "upple1" and "upple2".

The downcomer and lower plenum have also been modelled. The bypass coolant path is organized with the thermal-hydraulic components of the ICARE module.

The FRAGLOWE structure is used for corium fragmentation during corium slump into the lower plenum.

For rupture of lower head is used RUPTURE structure with selecting one from three criteria: CRIT 'TEMPERAT', CRIT 'FUSION' and CRIT 'MECHANIC'.

4 INITIAL PLANT CONDITIONS

Table 1: Initial plant design and steady-state plant conditions

Parameters	**Plant Design**	**ASTEC v2.2 b**
Reactor thermal power, MW	3000.0	3000.0
Primary pressure, MPa	15.7	15.7
Average coolant temperature at reactor outlet, K	593.15	593.65
Average coolant temperature at reactor inlet, K	563.0	562.0
Mass flow rate through one loop, kg/s	4400.0	4395.7
Pressure in SG, MPa	6.27	6.26
Pressure in main steam header (MSH), MPa	6.08	6.10
Steam mass flow rate through SG steam line, kg/s	408.0	409.0

5 RESULTS FROM CASE#1 AND CASE#2 CALCULATIONS

Table 2: Time of main events results

Events	**BC #1, Time, s**	**Case#2- OA at 980ºC, Time, s**
Transient initiation:	0.0	0.0
Break opening	0.0	0.0
MCPs stop	0.0	0.0
Reactor SCRAM	1.6	1.6
Feed water is disconnected	5.0	5.0
Turbine trip	2.0	2.0
Total Dryout of PRZ	12	12
Start of ACCU1&2 discharge	12.26	12.26
Start of ACCU3&4 discharge	12.34	12.34
Stop of ACCU1&2 discharge	98.13	98.13
Stop of ACCU3&4 discharge	103.56	103.56
Start of FPs release from fuel pellets (cladding failure)	504	504
Start of structural material release	526	526
First total core uncovery	680	680
First slump of corium with FPs in lower plenum	684	684
Core exit temperature reaches 980 °C (1253 K)	1270	1270
One high pressure pump (HPP) starts to inject in primary side	no	1272
One low pressure pump (LPP) starts to inject in primary side	no	1276
Lower head vessel failure	11187	no
End of calculation	15000	1472

In this section calculated results of both cases are presented (see Figure 2 to Figure 11). The first case (case#1) has presented most important events from the beginning of coolant leakage to the reactor vessel failure. In the second case (case #2) has assess the effectiveness of one HPP and one LPP at 980 ºC (1253 K) injection (the second entrance in SAMG when DG are available). The first entrance is at 650 ºC (923 K).

The observed initiating event is a LB LOCA with SBO at 0 s, in both cases.

The primary pressure drops sharply due to large loss of primary coolant inventory.

The pressurizer water level sharply decreases and PRZ is empty in a short time.

After initiating event all four HAs start to inject, when is reaching their sent point of 5.88 MPa (60 kgf/ cm^2), they depleted in short time due to the large loss of coolant.

The core uncovery depends on the RCS inventory depletion rate (governed by break area) and the rate of hydro accumulator's injection rate for both cases.

In the event of complete loss of reactor coolant system, the reactor core would heat up due to residual heat from the core.

The rapidly decreasing primary pressure and core coolant stagnation lead to deterioration of the core cooling in the beginning of the transient in both cases (Figure 2).

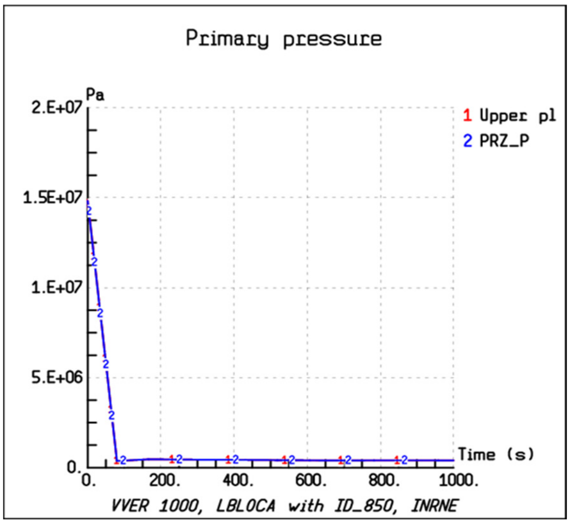


Figure 2: Primary side pressure (case #1)

Reactor vessel failure is observed only in the case without operator actions at 11 187 s. In the second case, the application of SAMG strategy successfully prevents the reactor core damage. The calculation in the second case is stopped after recovery of a water level in the vessel. The reactor core temperature evolution at the end of transient is presented in Figures 3 and 4.

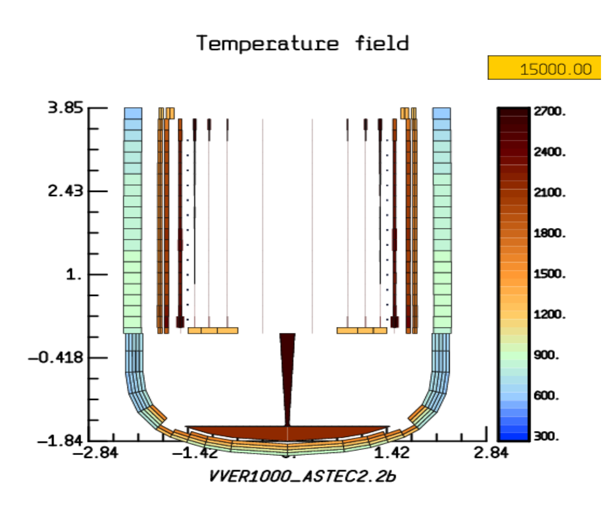


Figure 3: Reactor core temperature evolution at the end of transient (case #1)

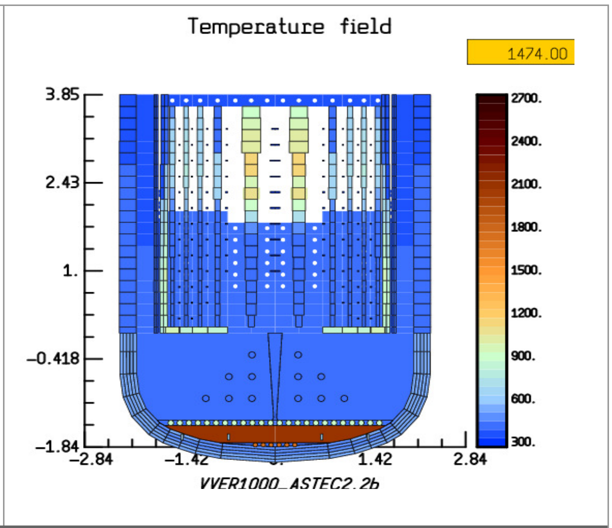


Figure 4: Reactor core temperature evolution at the end of transient (case #2)

The time for the SAMG activation is 1270 s, when the core exit temperature reaches 980°C (1253 K).

It is assumed availability of at least one DG for application of operator actions.

After depletion of the HAs, it increasing of core temperature at all levels including upper one (case#1) is observed. After partial dry out of the core upper part its cooldown by the steam, while the middle part of core is not cooldown due to miss of coolant. It allows further increasing of core temperature followed by destroying and melting of fuel elements at this area (see case#2).

As it is seen from the results in case#2 the core temperatures reach damaging conditions in the middle part of the reactor core before the application of operator action. The application of operator action prevents core from further damage progression.

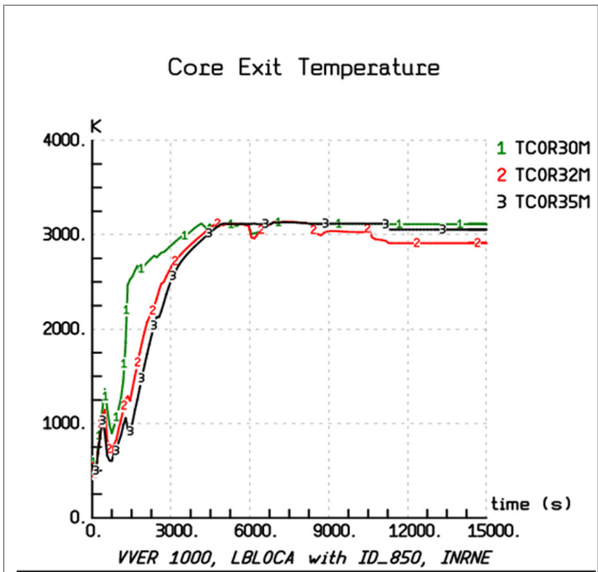


Figure 5: Core exit at 3.0 m, 3.2 m and 3.5 m temperature in the core (case #1)

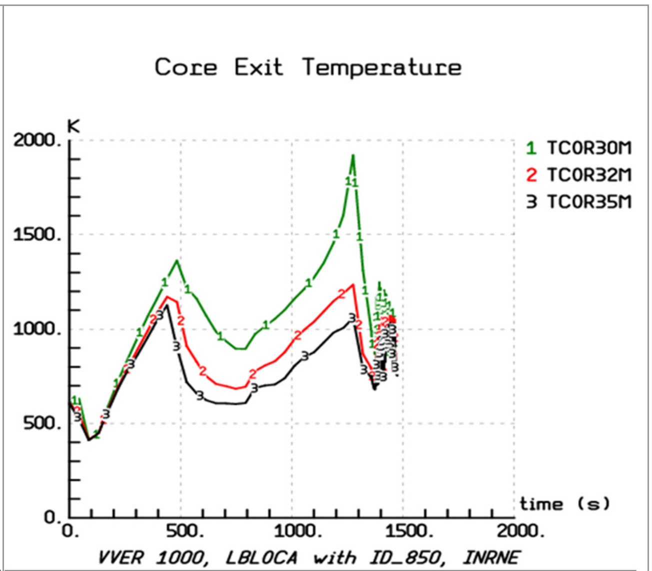


Figure 6: Core exit at 3.0m, 3.2m and 3.5m temperature in the core (case #2)

The maximal core exit temperature reached in both cases is given at Figures 5 and 6. Case#1 shows higher core temperature than 3000 K, while in the case#2 with start of one HPP and one LPP at 980 °C (1253 K) the core temperature reached two maximum values. The first one in first 500 s, after stop of HAs and the second one at 1270 s approx., when the temperature is 1677 °C (1950 K), when HPP and LPP start to inject. The reference temperature for activation of pumps is selected in the core at elevation 3.2 m (red).

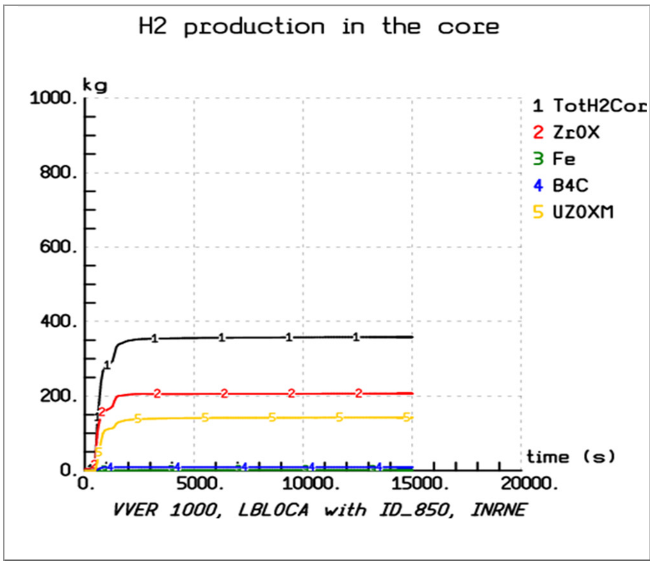


Figure 7: Hydrogen production in the core (case#1)

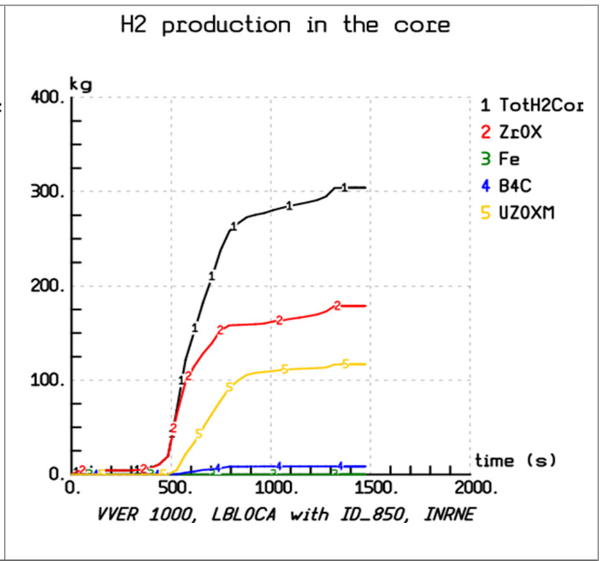


Figure 8: Hydrogen production in the core (case#2)

The maximum total hydrogen production in presented on Figures 7 and 8, in case#1 is 390 kg, which is observed significantly early of the transient at 100 s approx. while in the case#2 the maximal amount of hydrogen is 300 kg, which is observed at 1300 s. approx.

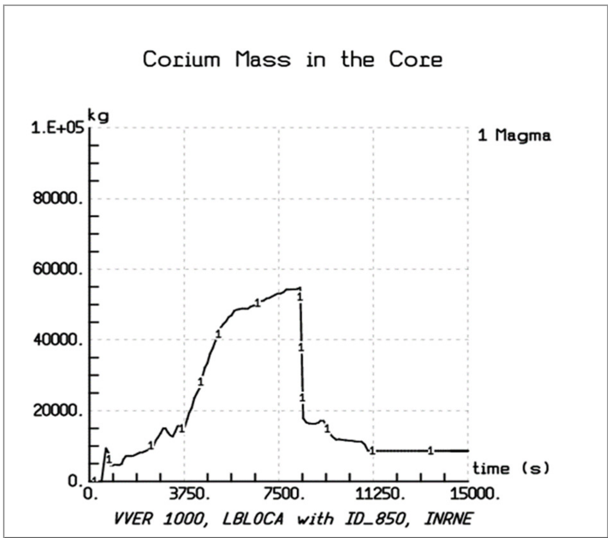


Figure 9: Corium mass in the reactor core (case#1)

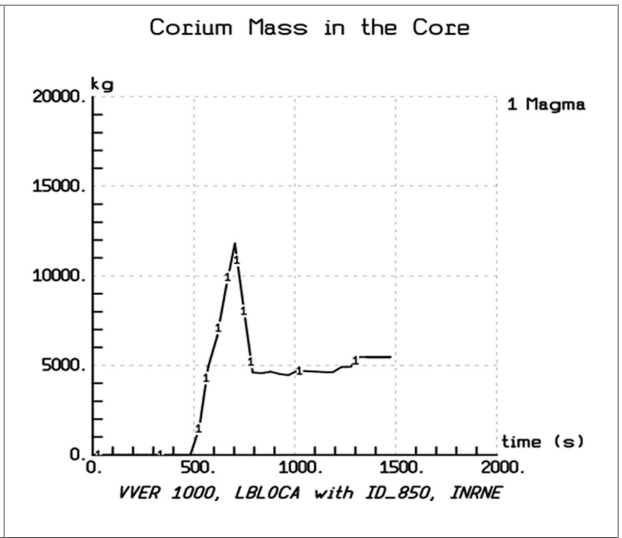


Figure 10: Corium mass in the reactor core (case#2)

The first corium slump in case#1 is observed at 684 s approx. and reaches the maximum amount of 55 000 kg corium mass at 8000 s approx. (see figure 9).

In case#2 the first corium slump is observed at 700 s approx. with partial melting and relocation of melt on the reactor vessel bottom before start of operator action (see Figure 10).

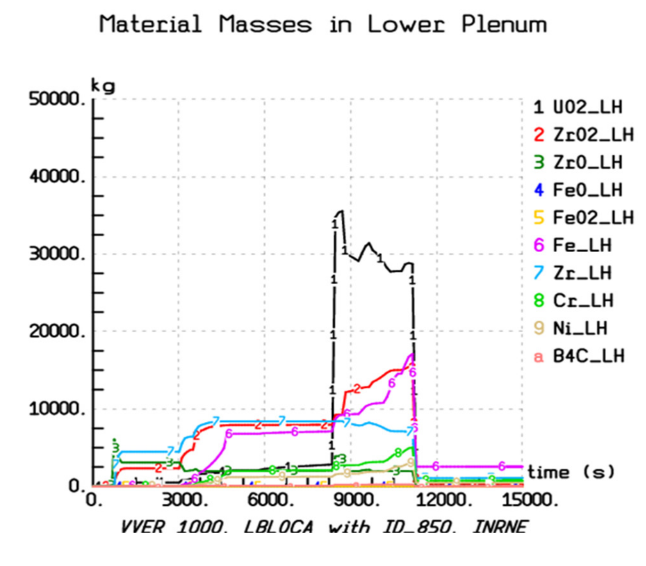


Figure 11: Corium mass in the lower plenum (case#1)

The core relocation observed in first case without operator action is presented on Figure 11. As it is seen the first big portion relocated UO_2 mass is observed at around 8 500 s of the transient, which causes significant increasing of primary pressure. The mass of other relocated core materials is given in the same graph. In case #1 the total observed mass of melt formation at the end of calculation is 86 t.

6 CONCLUSIONS

The performed calculations show that in the first calculation "without operator actions'' (case#1) the reactor core will melt with further failure of the reactor vessel. In this way selected initiating events lead to severe accident conditions. First cladding rupture occurs significantly later after termination of HAs work. Hydrogen generation reaches almost 400 kg. The total amount of corium to the bottom was around 86 t, which lead to vessel failure.

The calculation with application of operator actions based on SAMG strategies (case#2) shows that the operator can stop progression of core melt after injection of borated water, when the core temperature reached 980°C (1253 K). The performed operator actions successfully prevent the reactor vessel from failure, with partial melting and relocation of melt to the reactor vessel bottom.

ACKNOWLEDGMENTS

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