RISK ENGINEERING LTD.

Sensitivity Studies Related to MELCOR 2.1 Nodalizations for VVER-1000 (V320) Plant Models

Evgeni Borisov, Risk Engineering Ltd., MELCOR team, Bulgaria

5th Meeting of European MELCOR User Group (EMUG)
KTH - Albabova, Roslagstullsbaken 21, Stockholm, Sweden
May 2-3, 2013

Reliability, Safety and Management
Engineering and Software Development Services

Table of contents

Objectives

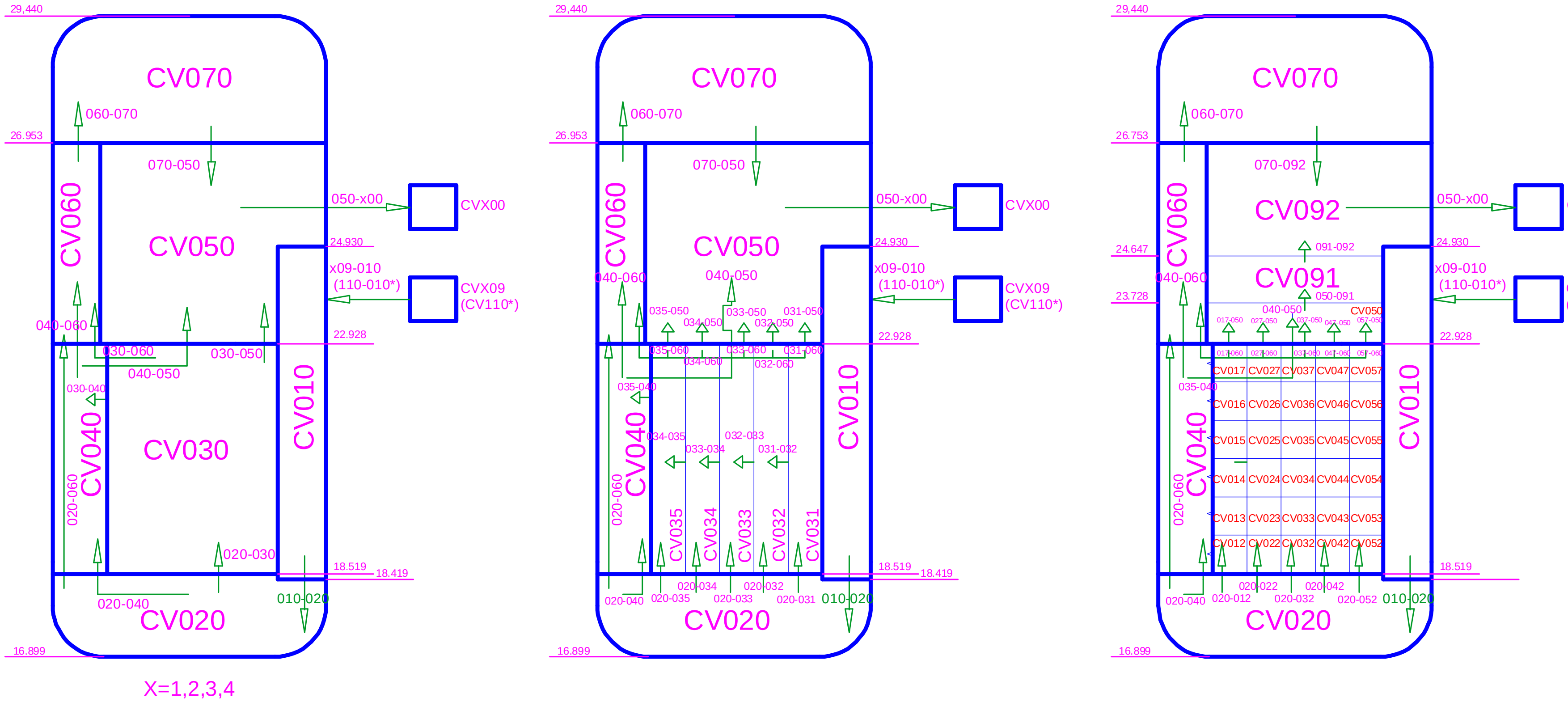
Main objectives of the presentation are as follows:

- To discuss the results from sensitivity studies which are performed in order to be analyzed WWER-1000 plant model response during severe accident progression when three different MELCOR 2.1 nodalizations for the core region are used. These three nodalizations are respectively with one, five and thirty hydrodynamic volumes in the reactor core region;
- To discuss the results from sensitivity studies which are performed in order to be analyzed WWER-1000 plant model response during severe accident progression when two different MELCOR 2.1 nodalizations for the steam generators secondary side are used. These two nodalizations are respectively with one and three hydrodynamic volumes for the steam generators secondary side;
- To represent and discuss various MELCOR 2.1 and/or plant model issues which have been identified during the performance of the sensitivity studies.

Variants of the nodalizations considered

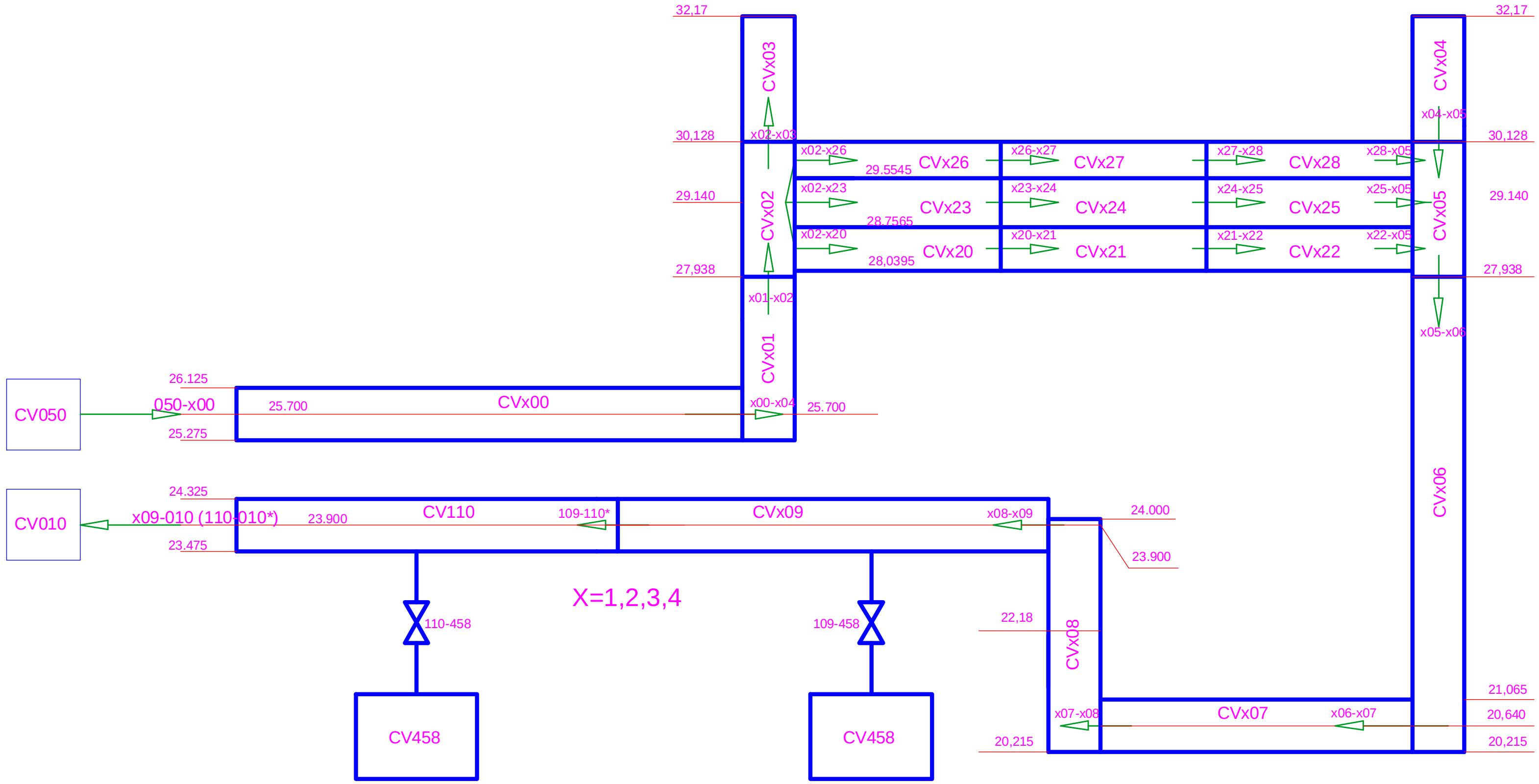
The nodalization schemes for the reactor pressure vessel and reactor internals, the primary loops and the steam generators secondary side are shown on Figure 1, Figure 2 and Figure 3 respectively.

Variants of the nodalizations considered – cont'd (1)



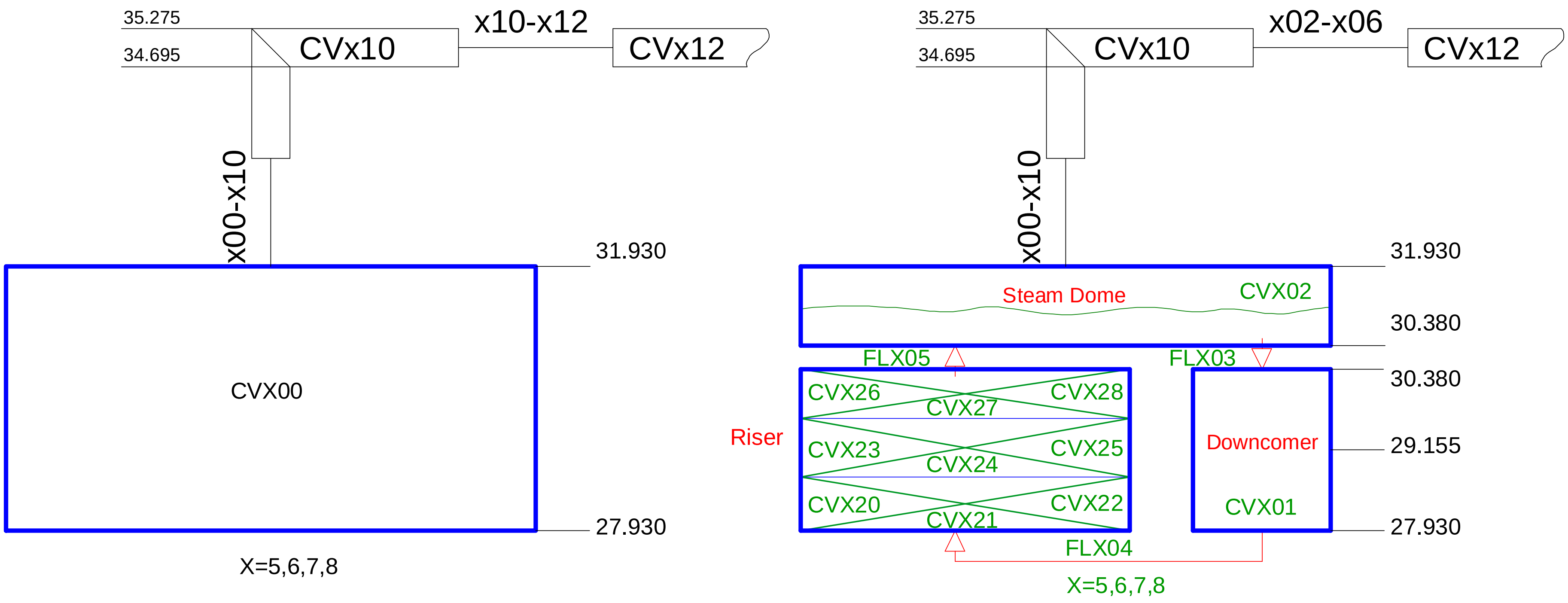
- **Figure 1: Reactor pressure vessel and reactor internals nodalizations (for all the cases 5 radial rings in the COR package are modeled)**

Variants of the nodalizations considered – cont'd (2)



- **Figure 2: Primary loops nodalization (4 separate loops are modeled)**

Variants of the nodalizations considered – cont'd (3)



- **Figure 3: Steam generators secondary side nodalizations**

Conditions and assumptions

For the performance of the sensitivity studies, the following conditions and assumptions take place:

- Subversion 5026 of MELCOR 2.1 has been used for the calculations;
- For the flow paths which connect the reactor lower plenum to the reactor core, flow paths inside the core, flow path to the reactor core bypass and the artificial flow paths between the core and the core shroud, the flow blockage option has been activated (FL_BLK). The default value of the minimum porosity which is used in calculation of the flow resistance is chosen. The exception of that assumption is a case with double ended break of a main circulation pipeline (case 3B from Table 2) for which this coefficient is set to 0.5 in order to avoid failure of MELCOR 2.1;
- No safety systems are available with the exception of the case with reactor pressure vessel bottom break (as initiating event);
- HS degasing option is activated (HS_DG) – for the steel structures inside the vessel;
- No operator actions are considered.

Cases analyzed, initial and boundary conditions

For the purposes of sensitivity studies, the following cases have been selected:

- Total loss of power supply to the unit – For WWER-1000 (V320) this transient is characterized by high primary pressure and relatively slow primary water inventory decrease. Input decks with 1, 5 and 30 volumes in the reactor core are used. One and three volumes for the steam generators secondary side are separately used;
- Double ended break of a main circulation pipeline with DN 2x850 mm (cold leg break) – this case is characterized by the most dynamic change in the primary side parameters and very fast degradation of the core in case of unavailability of safety systems. Input decks with 1, 5 and 30 volumes in the reactor core are used. One volume for the steam generators secondary side is used because the secondary side influence on the severe accident progression for that case is not expected to be significant;
- Reactor pressure vessel partial break with DN 1130 mm (cross section area around 1.0 m^2) with active and passive safety systems availability – this case is analyzed in order to assess the core blockage behavior for 1, 5 and 30 volumes in the reactor core region with safety systems availability. One volume for the steam generators secondary side is used, because the secondary side influence on the severe accident progression for that case is not expected to be significant;

Cases analyzed, initial and boundary conditions – cont'd (1)

- Middle LOCA of a cold circulation pipeline (close to the reactor vessel) with DN60 mm – this case is analyzed in order to assess the reactor installation response in case of severe accident progression as a result of middle LOCA. Input decks with 1, 5 and 30 volumes in the reactor core are used. One and three volumes for the steam generators secondary side are separately used;
- Primary to secondary LOCA with DN 43 mm (PRISE 43 mm) – this case is specifically analyzed in order to be assessed the secondary side influence on the primary parameters in severe accident conditions.

Summary information for the cases which have been selected for the sensitivity studies is presented in Table 1.

Cases analyzed, initial and boundary conditions – cont'd (2)

Table 1: Summary information for the cases analyzed

Case	Initial Condition	Safety systems availability	Variant	Number of Core/SG volumes
1. Station blackout	Nominal Power	No	1A	1V/1V
			2A	5V/1V
			3A	30V/1V
			4A	30V/3V
2. LB LOCA with DN2x850 mm	Nominal Power	No	1B	1V/1V
			2B	5V/1V
			3B	30V/1V
3. RPV bottom partial failure with DN 1130 mm	Nominal Power	Yes (one train from each safety system)	1C	1V/1V
			2C	5V/1V
			3C	30V/1V
4. MB LOCA with DN60 mm	Nominal Power	No	1D	1V/1V
			2D	5V/1V
			3D	30V/1V
			4D	30V/3V
5. PRISE with DN43 mm	Nominal Power	No	1E	30V/1V
			2E	30V/3V

Important parameters for the sensitivity studies

For the sensitivity studies performed, the following parameters during the severe accident progression are analyzed:

- CPU time consumption (tCPU) – up to the moment of vessel breach;
- Total amount of hydrogen generated in the reactor core (COR-DMH2-TOT);
- Onset of gap release (tGR);
- Time when the maximal fuel cladding temperature reaches 1200^{o}C (tCD);
- Onset of reactor core degradation (tDEG);
- Onset of UO_2 relocation into the reactor lower plenum (tMUO2);
- Total mass of UO_2 relocated into the lower plenum before the vessel breach (MUO2);
- Onset of the reactor pressure vessel breach (tVBR);
- Total amount of molten material ejected to the reactor cavity (COR-MEJEC-TOT);
- Maximal temperature of the hot legs (Thl_max) – important for station blackout scenarios due to the creep rupture phenomenon (it is assessed 30 min before the vessel breach because HPME/DCH is concurrent to the creep rupture phenomenon);

Summary results from the sensitivity studies

Table 2: Summary results from the sensitivity studies performed – part 1

Case	Variant	Number of Core/SG volumes	COR-DMH2-TOT [kg]	tCPU [h]	tStZr [s]	tGR [s]	tCD [s]	tDEG [s]
1. Station blackout	1A	1V/1V	582	10.8	10500	10946	12500	15430
	2A	5V/1V	912	11.3	11500	11691	15000	24435
	3A	30V/1V	760	16.9	11000	11347	13000	15844
	4A	30V/3V	668	17.5	10500	10727	12500	14997
2. LB LOCA with DN2x850 mm	1B	1V/1V	114	10.1	5	40	160	800
	2B	5V/1V	149	10.0	5	45	160	800
	3B	30V/1V	131	19.8	5	47	240	720
3. RPV bottom partial failure with DN 1130 mm	1C	1V/1V	95	108	6	48	175	797
	2C	5V/1V	208	157	6	48	175	807
	3C	30V/1V	2.3	331*	120	278	NO	NO
4. MB LOCA with DN60 mm	1D	1V/1V	273	11.2	2000	1800	2500	2826
	2D	5V/1V	263	9.8	2000	2000	2500	3341
	3D	30V/1V	295	16.5	2000	2077	2500	3113
	4D	30V/3V	246	17.4	2000	2038	2500	3067
5. PRISE with DN43 mm	1E	30V/1V	454	22.3	8000	8417	9500	10576
	2E	30V/3V	401	22.9	8000	8242	9500	10271

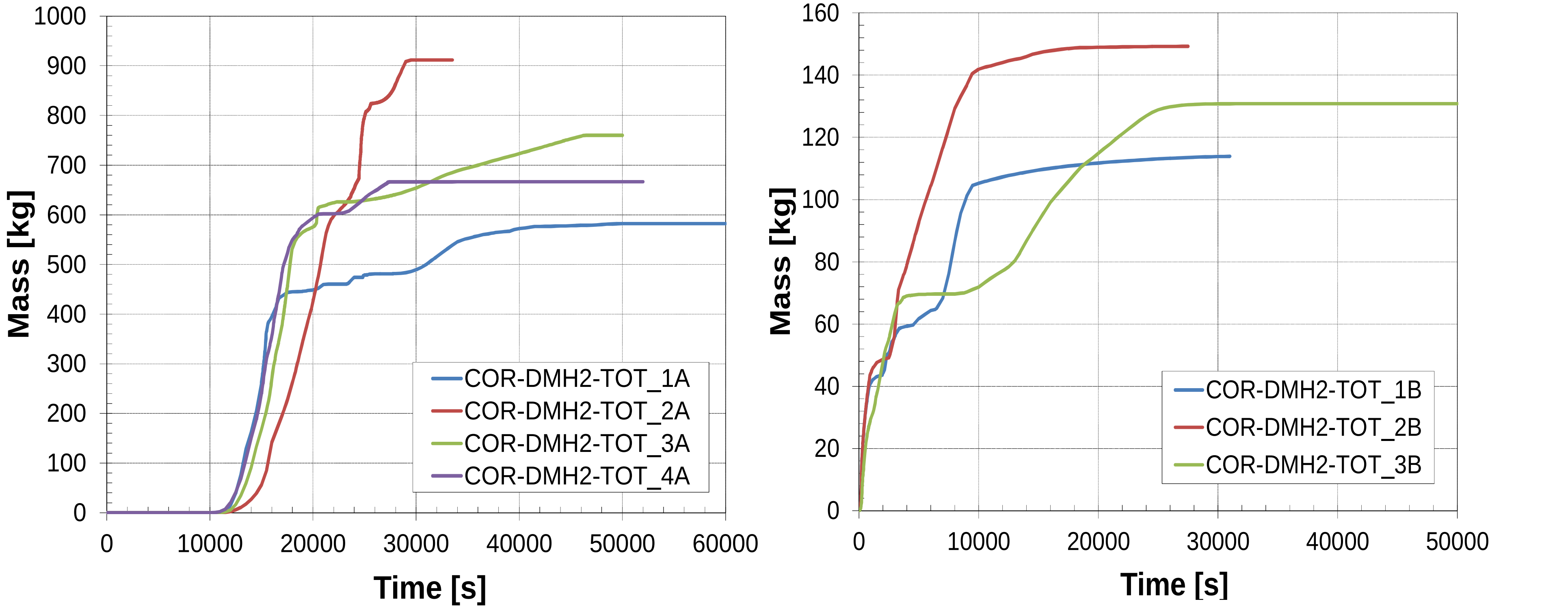
*Calculated to the 24-th h (accident progression time) after the accident initiation

Summary results from the sensitivity studies – cont'd (1)

Table 2: Summary results from the sensitivity studies performed – part 2

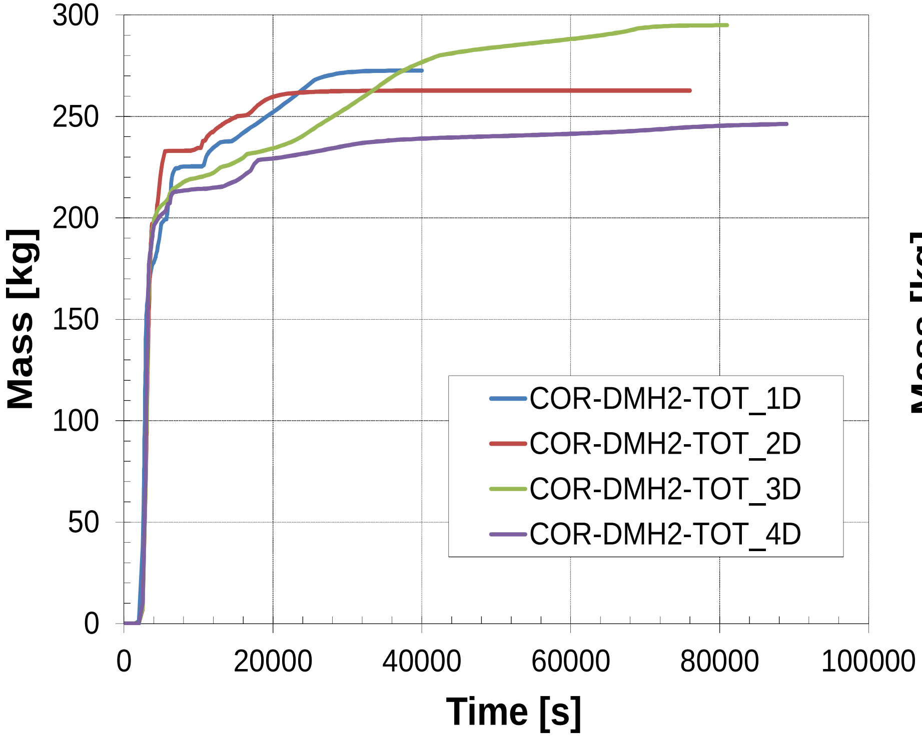
Case	Variant	Number of Core/SG volumes	tMUO2 [s]	MUO2 [tons]	Thl_max ** [K]	tVBR [s]	COR-MEJEC-TOT [tons]
1. Station blackout	1A	1V/1V	15684	69	1260	25236	195
	2A	5V/1V	24490	52	1428	25615	218
	3A	30V/1V	16389	63	1015	22351	222
	4A	30V/3V	15946	53	994	20525	194
2. LB LOCA with DN2x850 mm	1B	1V/1V	1940	77	Not needed	8166	154
	2B	5V/1V	2470	74	Not needed	9024	178
	3B	30V/1V	2480	78	Not needed	7983	157
3. RPV bottom partial failure with DN 1130 mm	1C	1V/1V	797	83	Not needed	22350	144
	2C	5V/1V	9208	76	Not needed	40500	114
	3C	30V/1V	NO	NO	Not needed	NO	NO
4. MB LOCA with DN60 mm	1D	1V/1V	5704	70	Not needed	12845	186
	2D	5V/1V	4290	77	Not needed	14936	173
	3D	30V/1V	5923	72	Not needed	12057	156
	4D	30V/3V	5506	76	Not needed	13258	162
5. PRISE with DN43 mm	1E	30V/1V	10698	66	Not needed	17972	194
	2E	30V/3V	10422	70	Not needed	18235	180

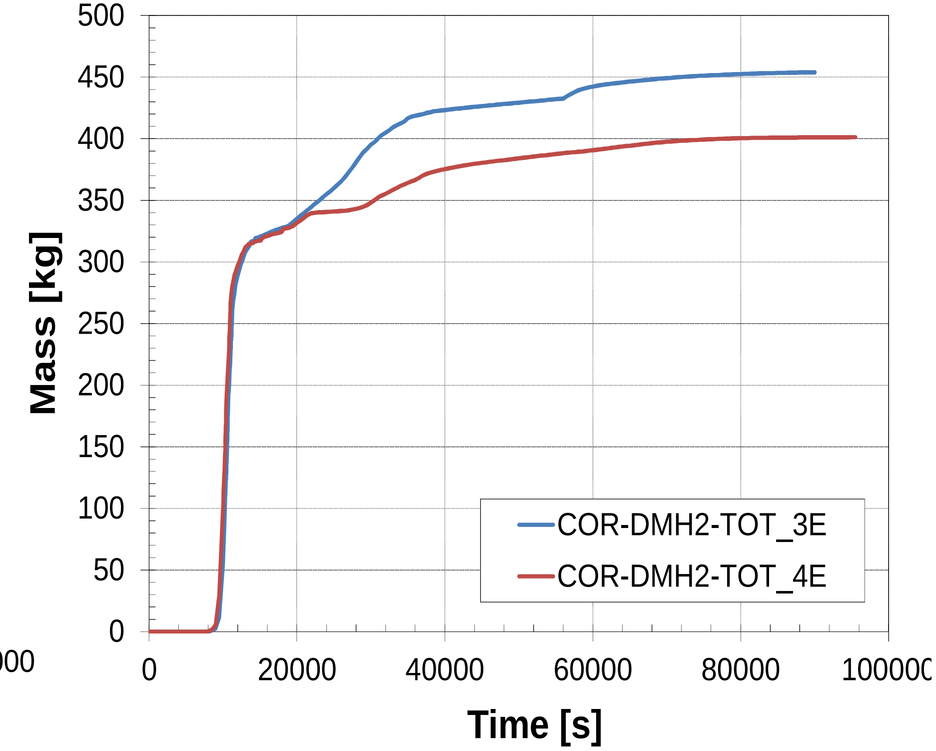
Summary results from the sensitivity studies – cont'd (2)



- **Figure 4: Total amount of the hydrogen generated for the in-vessel phase of severe accident (cases A, B,)**

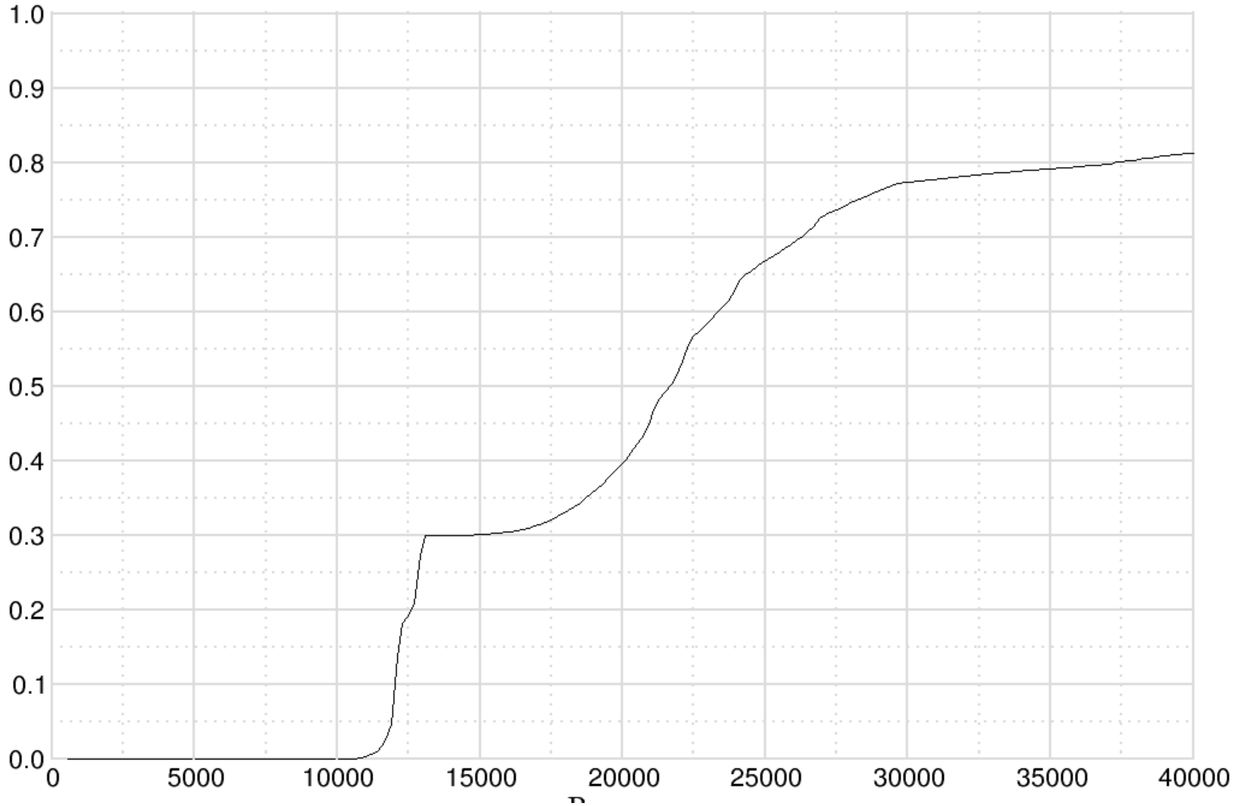
Summary results from the sensitivity studies – cont'd (3)





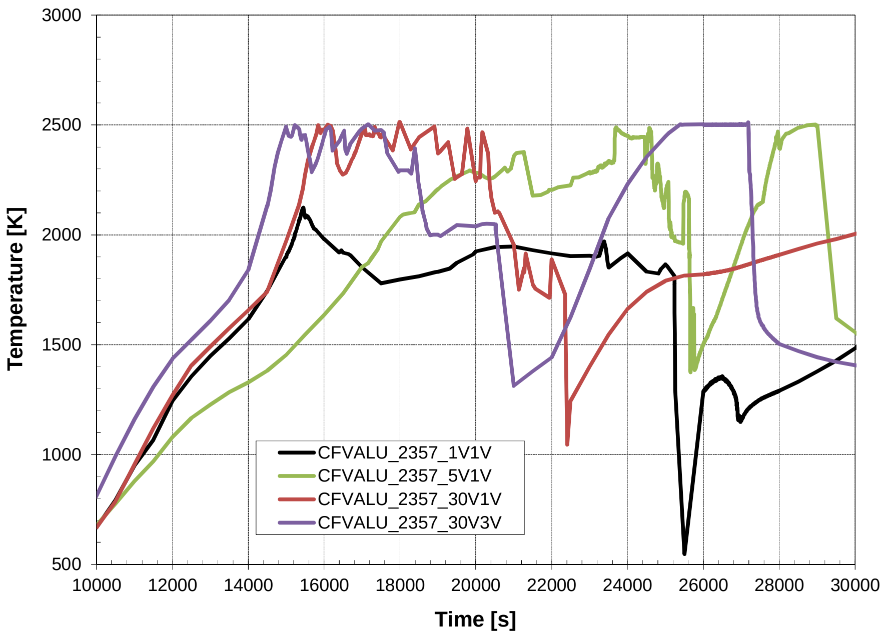
- **Figure 5: Total amount of the hydrogen generated for the in-vessel phase of severe accident (cases D, E)**

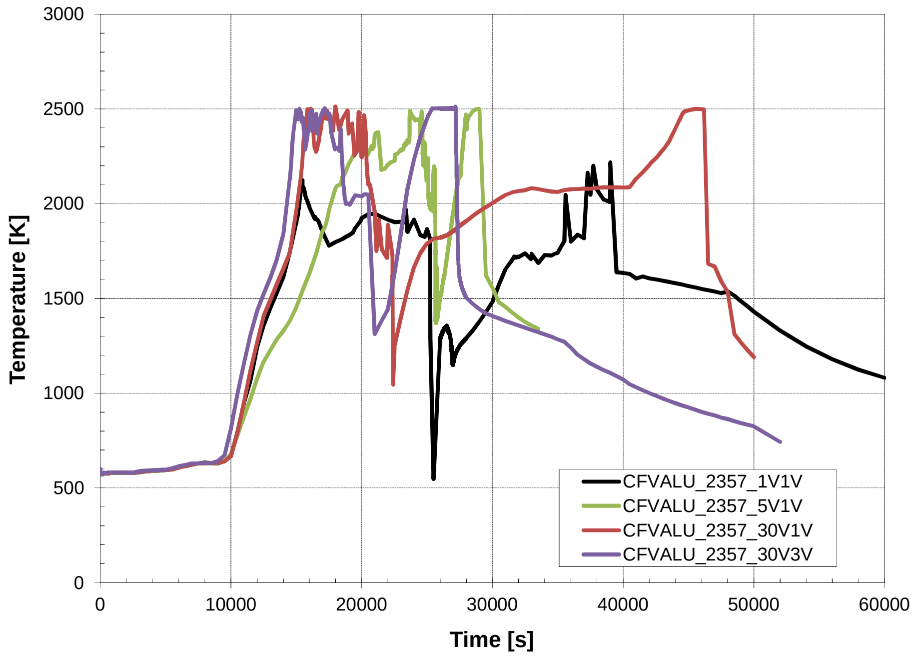
Summary results from the sensitivity studies – cont'd (4)



- **Figure 6: Total amount of the hydrogen generated – RELAP/SCDAP – Mass (tons) vs. Time (s) [2]**

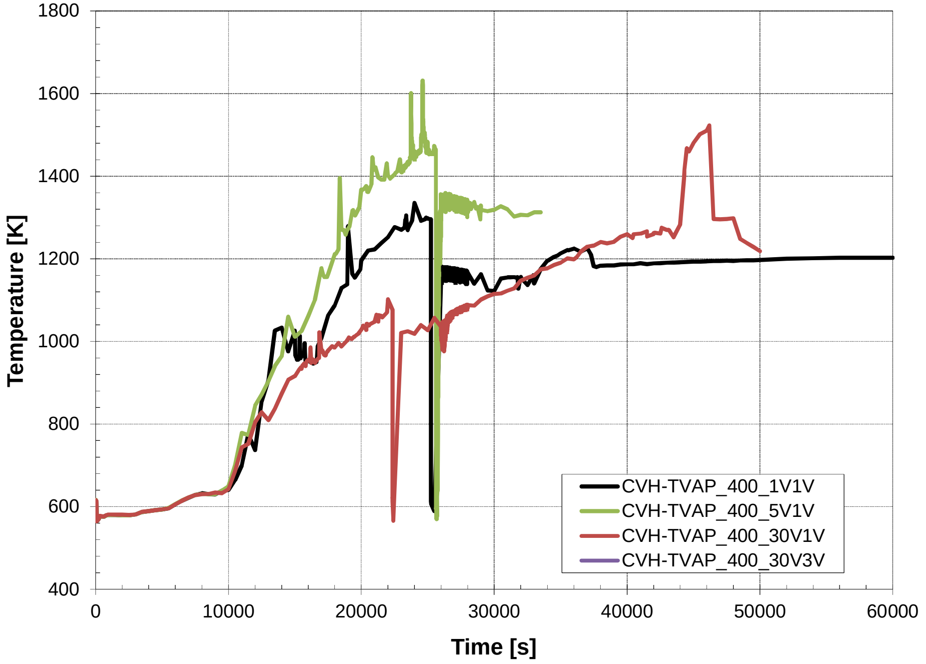
Summary results from the sensitivity studies – cont'd (5)

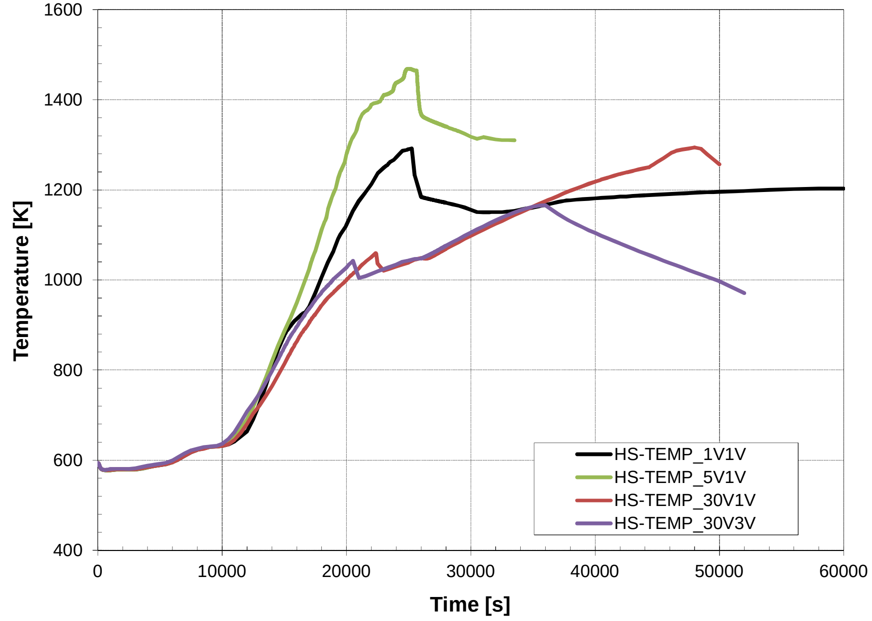




- **Figure 7: Maximal gas temperature in the core – station blackout cases**

Summary results from the sensitivity studies – cont'd (6)





- **Figure 8: Hot legs gas temperatures (left) and hot legs metal temperature (right)**

Issues identified during the sensitivity studies – Issue 1

Issue 1: Related to station blackout scenario (5 volumes in the core region):

When nodalization scheme with 5 volumes in the core is used, then the core degradation starts immediately after the vessel breach or very late after that moment which is not physically accurate. This leads to initial ejection of a very small amount of molten material (mainly steel – about 500 kg) and the peak of the molten corium ejection starts about 4000 s after the vessel breach (see COR-MEJEC-TOT_2B_1 on Figure 9). The root cause of that issue might be related to erroneous activation of the lower head mechanical model (by the code or due to user mistakes). It is not clear so far what the exact reason is.

Issues identified during the sensitivity studies – Issue 1 (cont'd (1))

This issue has been overcome by the following ways:

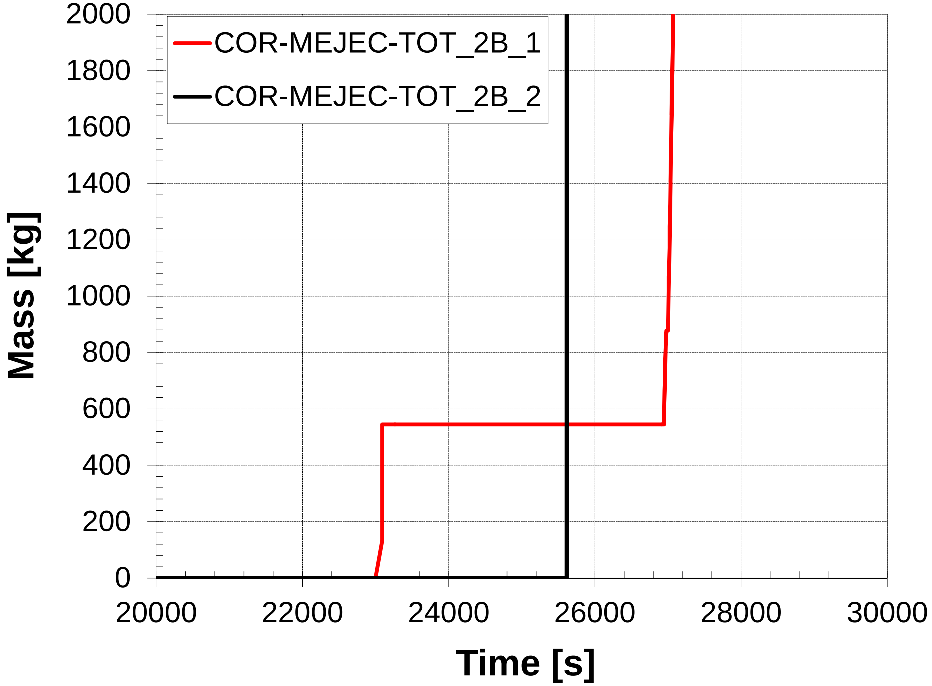
- The lower head mechanical model is switched off by the sensitivity coefficient 1600 (3) which is set to 1.0E10. When the molten core material in the lower plenum reaches around 50-70 tons and there is molten material into the lower plenum region below the barrel perforated bottom (around 2.5 t), then SC 1600 (3) is set back to its default value of 1.0E3. The lower head fails and the molten corium ejection seems to be quite reasonable (see COR-MEJEC-TOT_2B_2 on Figure 9). For Variant 2A (from Table 2) this approach has been applied;
- Nodalization scheme with 30 hydrodynamic volumes in the core – for that nodalization this issue does not appear at all.

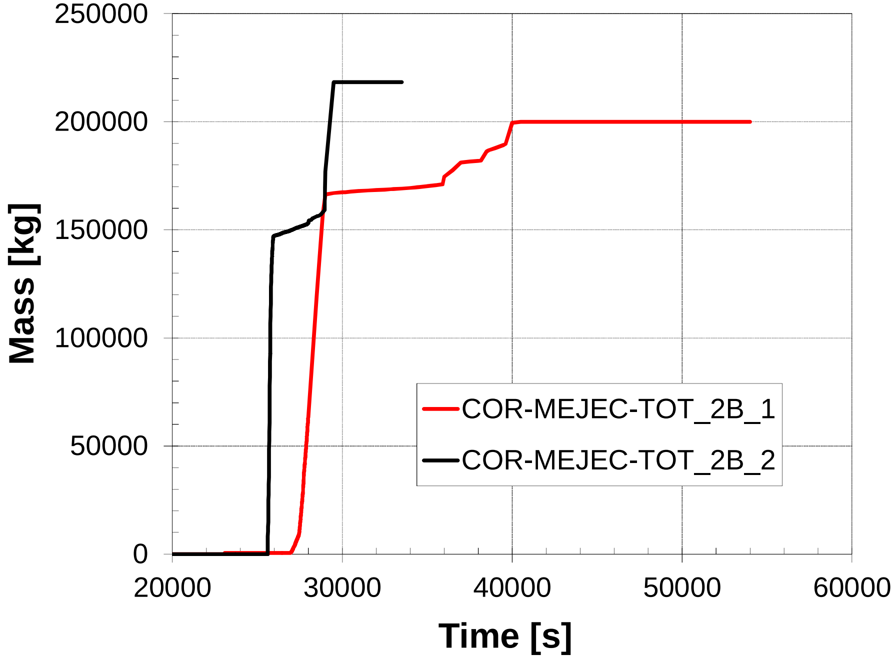
Issues identified during the sensitivity studies – Issue 1 (cont'd (2))

Depending on the time step this issue might cause additional problems such as:

- Reactor vessel breach with a very small amount of corium ejected – 1.0E-38 kg followed by a large corium ejection several hundred seconds after the vessel breach;
- Generation of error massage: Cavity Overfilled (an attempt to be ejected physically impossible amount of molten material – around 900 tons). This used to happen for the MELCOR 2.1 subversions before subversion 5026 for our WWER-1000 plant model specifically.

Issues identified during the sensitivity studies – Issue 1 (cont'd (3))





- **Figure 9: Mass of molten corium ejected – left hand side (close plan)**

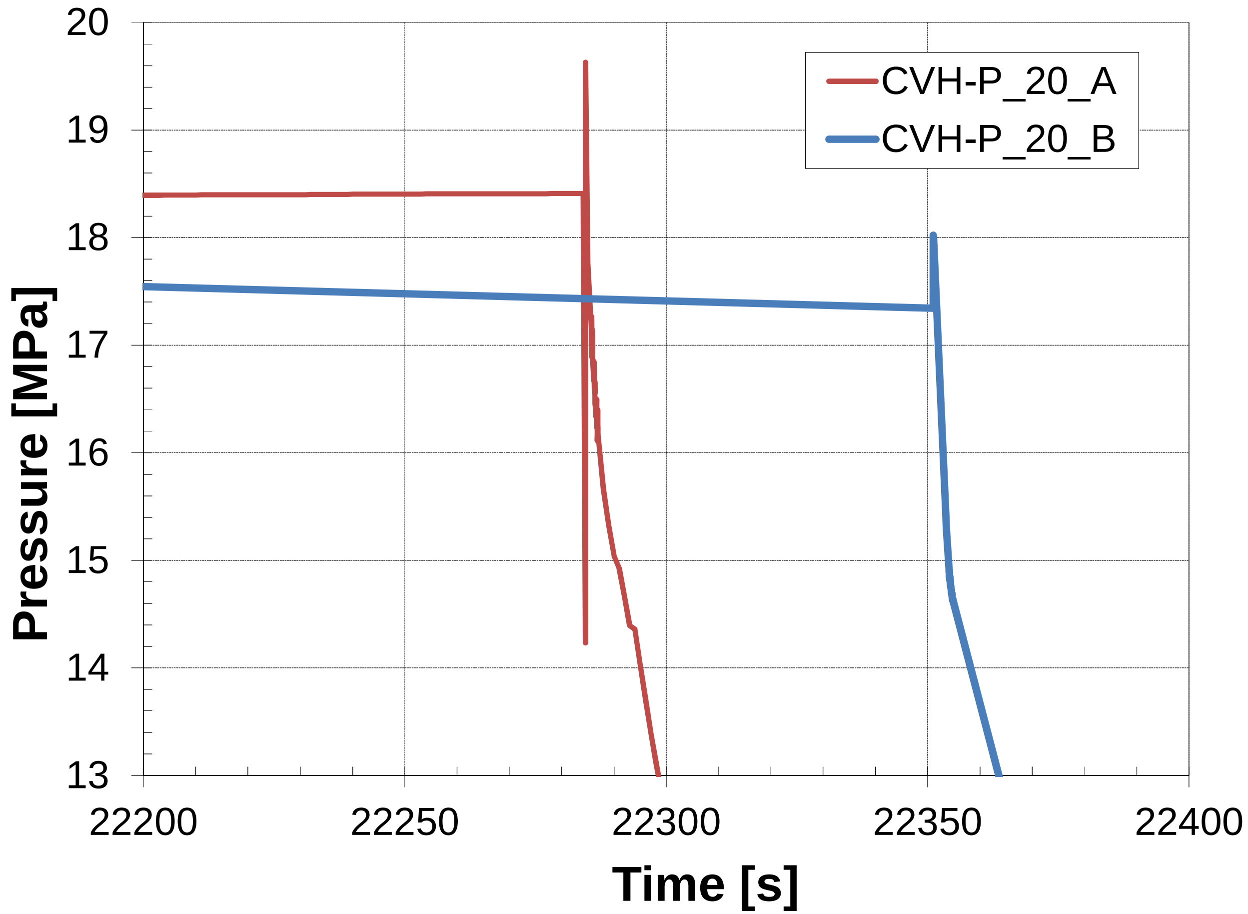
Issues identified during the sensitivity studies – Issue 2

Issue 2: Related to station blackout scenario (5 and 30 volumes in the core region):

When nodalization scheme with 5 or 30 volumes in the core is used, then, at the moment of the reactor pressure vessel breach, the primary pressure oscillation between 14 MPa and 20 MPa occurred (see CVH-P_20_A on Figure 10). It is followed by a message for lowed head failure due to overpressure. This issue has been overcome by the following ways:

- 500-1000 s before the vessel breach the sensitivity coefficient 1505 (1) was set to 1.0 (core blockage porosity coefficient) (see CVH-P_20_B on Figure 10);
- When 3 volumes for the steam generators are used then this issue does not appear at all.

Issues identified during the sensitivity studies – Issue 2 (cont'd (1))



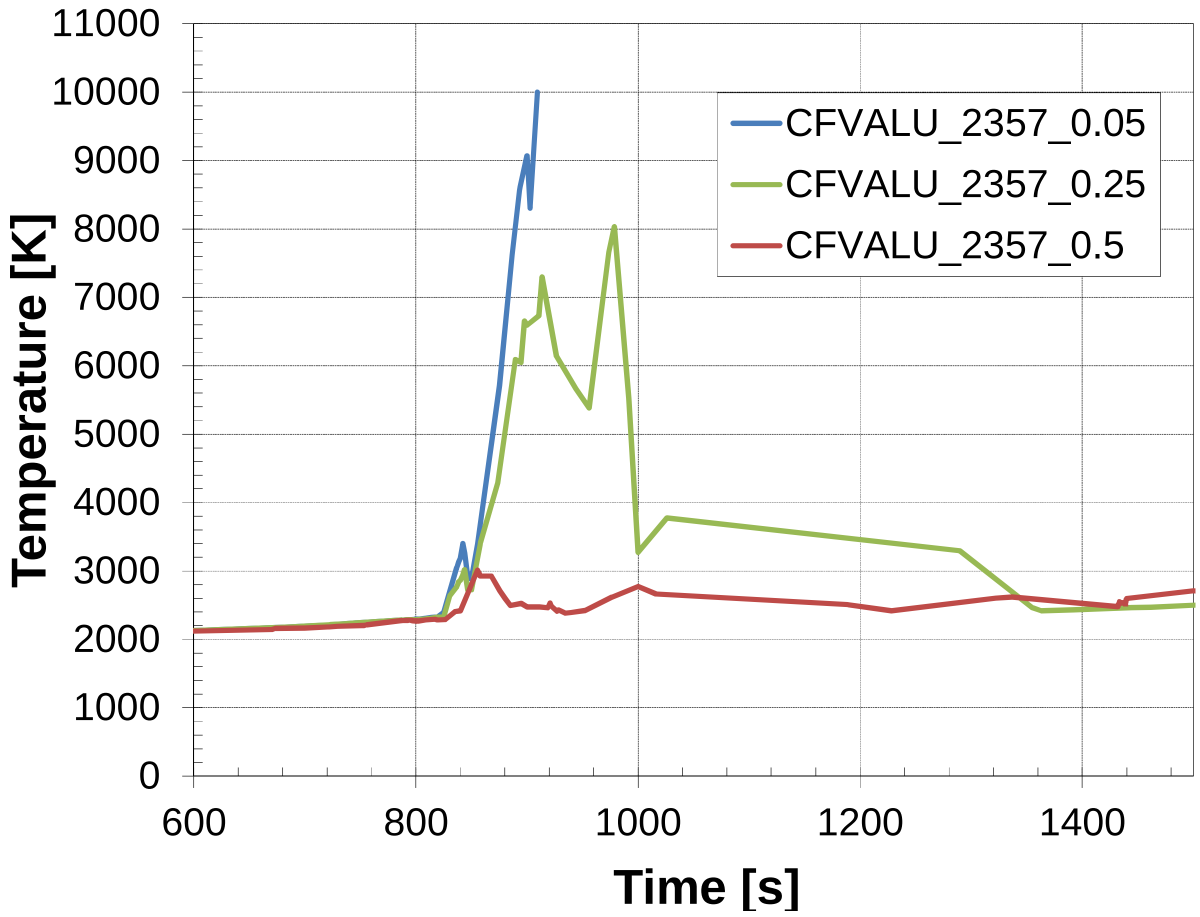
- **Figure 10: Reactor lower head pressure before and shortly after the vessel breach**

Issues identified during the sensitivity studies – Issue 3

Issue 3: Related to LB LOCA with DN 2x850 mm (30 volumes in the core region)

- When nodalization scheme with 30 volumes in the core is used then a very large temperature peak around 10 000 K in a volume from the core region occurs and therefore MELCOR 2.1 fails (see CFVALU_2357_0.05 on Figure 11). This issue is overcome by setting sensitivity coefficient 1505 (1) to 0.5. Values of that coefficient equal to 0.05 (by default), 0.1 and 0.25 lead to high temperature peak in the core and code failure.

Issues identified during the sensitivity studies – Issue 3 (cont'd (1))



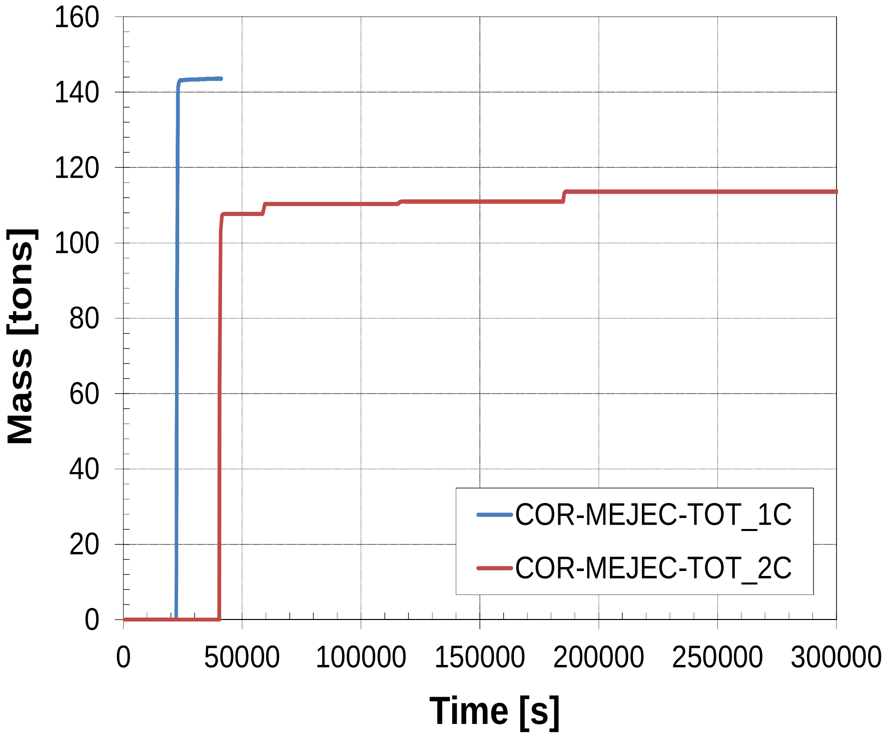
- **Figure 11: Maximal gas temperatures in the core for Issue 3 (right) – blockage porosity 0.05, 0.25 and 0.5**

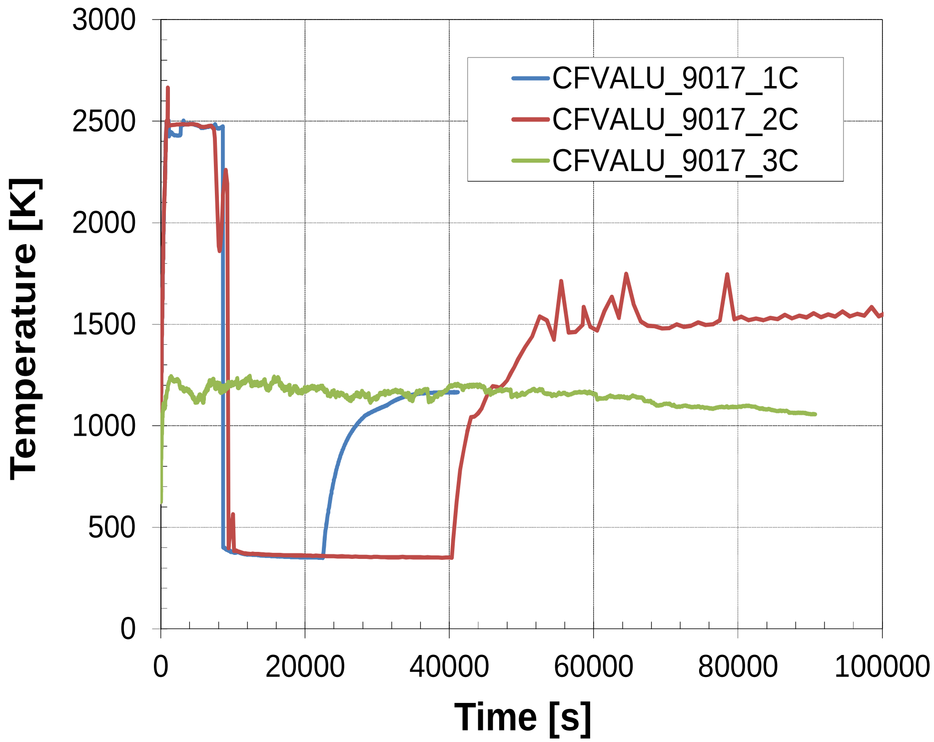
Issues identified during the sensitivity studies – Issue 4

Issue 4: Related to RPV bottom partial failure with DN 1130 mm (all variants);

For that initiating event, quite unexpected results have been obtained. For the variant with 1 and 5 hydrodynamic volumes in the core, the reactor vessel breach occurs about 22350 s and 40500 s after the accident initiation respectively (see Figure 12 (left hand side)). For the case with 30 volumes, core degradation does not occur at all (to ensure that, the calculation is extended to 24h) (see Figure 12 (right hand side)). At that moment, no reasonable explanation for these results has been found.

Issues identified during the sensitivity studies – Issue 4 (cont'd)





- **Figure 12: Mass of molten corium ejected (left) and maximal fuel cladding temperature (right) for Issue 4**

Conclusions

As a result of the sensitivity studies performed, the following conclusions can be drawn:

- The general progression of the severe accident for most of the cases considered is reasonable. The exceptions are the cases with RPV bottom break (with DN 1130 mm). The obtained results are quite different and it is difficult to draw a clear conclusion about them. This causes great uncertainty in the containment event trees development for these cases;
- Most of the issues which have been identified are related to the nodalization schemes with 5 and 30 hydrodynamic volumes into the core region;
- The variants with 1 hydrodynamic volume in the core have not caused any issues and the code run quite stable. This variant leads to the lowest amount of hydrogen generated for the in-vessel phase of the severe accident in case of station blackout scenario (case 1A). According to the results for the same initiating event which are generated by RELAP/SCDAP, the total amount of hydrogen generated for that phase is around 800 kg (see Figure 6). So the lowest amount of hydrogen for that case may or may not be physically accurate. As it can be seen from Table 2, the COR-DMH2-TOT parameter for cases 2A ÷ 4A is significantly higher than in case 1A which can be explained by the possibility for in-core circulation of water-steam mixture and the different core blockage behavior (more volumes and more flow paths available in the core for 5 and 30 volumes nodalizations). For case 2A, the largest value for the COR-DMH2-TOT parameter comes from the latest core relocation into the lower head and therefore latest vessel breach;

Conclusions – cont'd

- For LB LOCA with DN 2x850 mm, MB LOCA with DN 60 mm and PRISE 43 mm, the total amount of hydrogen generated into the core during the in-vessel phase does not differ significantly for the nodallizations with 1, 5 and 30 volumes in the core. Variant 3B is characterized by physically impossible gas temperature behavior in the core when the minimal blockage fraction is less than 0.5;
- For the cases 1A and 1B, the maximal hot legs metal temperatures are significantly higher than in cases 1C and 1D. This result is important when one considers creep rupture phenomenon which is more likely to occur for the hot legs than for the pressurizer surge line or SG tube (in the cases where none of the loop seals is cleared);

References

1) Actualization of PSA level 2 for KNPP (Kozloduy NPP, Bulgaria) units 5 and 6 (full power and shut-down), Risk Engineering Ltd (project is in progress);
2) Accident Management Guidelines and Procedures: Improvement of the Emergency Documentation for Ukrainian NPP, Risk Engineering Ltd. (project is in progress)

CONTACT DETAILS

Headquarters:
10, Vihren str.
Sofia 1618
Bulgaria
Tel. + 359 2 8089 703
Fax: +359 2 9507 751
riskeng@riskeng.bg
www.riskeng.bg

THANK YOU!