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Challenges to the Design of Containment Filtered Venting Systems at NPP

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Abstract. Severe accidents (SA) may result in pressure and temperature increase leading to containment failure and uncontrolled release of radioactive products to the environment. Containment over-pressurization can be prevented by the operation of a Containment Filter Venting System (CFVS) intended to actuate within the specific SA conditions. However, the particular design solution and especially the sizing of appropriate Containment Filter Venting System require precise information regarding the accident progression and parameters. Such information may be obtained only by detailed assessment of each phase of the severe accident considering the specific reactor technology. Therefore, a study was performed in order to evaluate the most challenging conditions and the most suitable solution for implementation of a system for filtered venting of the containment taking into account the uncertain nature of the accidents and the limitations of the mathematical simulations.

The current paper presents the main results from the abovementioned study on the influence of the severe accident conditions, including the specific containment environment effects, to the design and sizing of Containment Filter Venting System.

The study includes the selection of a bounding case and the initial conditions for simulation of a severe accident scenario which is expected to pose the most stringent requirements to the CFVS. Evaluation of the Molten Core Concrete Interaction (MCCI) parameters and analysis of system performance during the severe accident progression is furthermore performed. The main parameters of the accident scenario under evaluation are the timing of the vessel failure and the containment design limit pressure achievement, hydrogen production during the accident and its influence on the system operation.

The accuracy of predictions of the severe accident parameters (containment pressure and temperature, fission product mass concentration at different stages of accident, modelling the characteristics of aerosols in the containment, etc.) obtained using the MELCOR 1.8.5 model, is also discussed.

Keywords: Containment Filtered Venting System, Severe Accidents, LB LOCA, MELCOR, VVER-1000, Aerosol

1 Introduction

The last physical barrier between the radioactive materials and the environment is the containment structure of the Nuclear Power Plants (NPP). It also protects the reactor against external events and provides radiation shielding during operational states and accident conditions.

In case of a severe accident, the radioactive materials may reach the environment in case the containment structure is damaged and/or bypassed. The result from the recent "stress-tests" performed for all European reactors after the accident at the Fukushima Dai-ichi NPP in Japan highlighted the need for safety improvements. The majority of the improvements intended to be implemented consider beyond-design-basis natural hazards and the resulting effects on plant systems and barriers from an extended loss of electrical power and heat removal capability [1,2].

Moreover, the stress tests results emphasize the need for strengthening of the containment safety and directly stipulate that *"Containment venting must be considered via the filters designed for severe accident conditions, such as to ensure a sufficiently long venting time"* [3].

Therefore, WorleyParsons initiated a study for evaluation of the most suitable CFVS technology able to operate under the harsh conditions of the severe accident. The correct implementation of a CFVS system will

- Prevent containment over-pressurization;
- Minimize the radioactive releases into the environment and decrease the off-site doses;
- Avoid or significantly decrease any land contamination;
- Reduce the concentration of hydrogen and other non-condensable gases inside containment.

The current knowledge on existing mitigation systems intended to address containment overpressure cover mainly two types of design – wet scrubber [4] and dry-filtration design. In both options the CFVS's operation avoids containment overpressure failure and at the same time provides more flexibility to perform accident management measures. Differences between the two approaches are mostly related to installation and operation of the systems.

As the most promising and innovative approach, the application of CFVS based on the operation of dry modern industrial filters was identified as justified below. The dry filtration system ensures

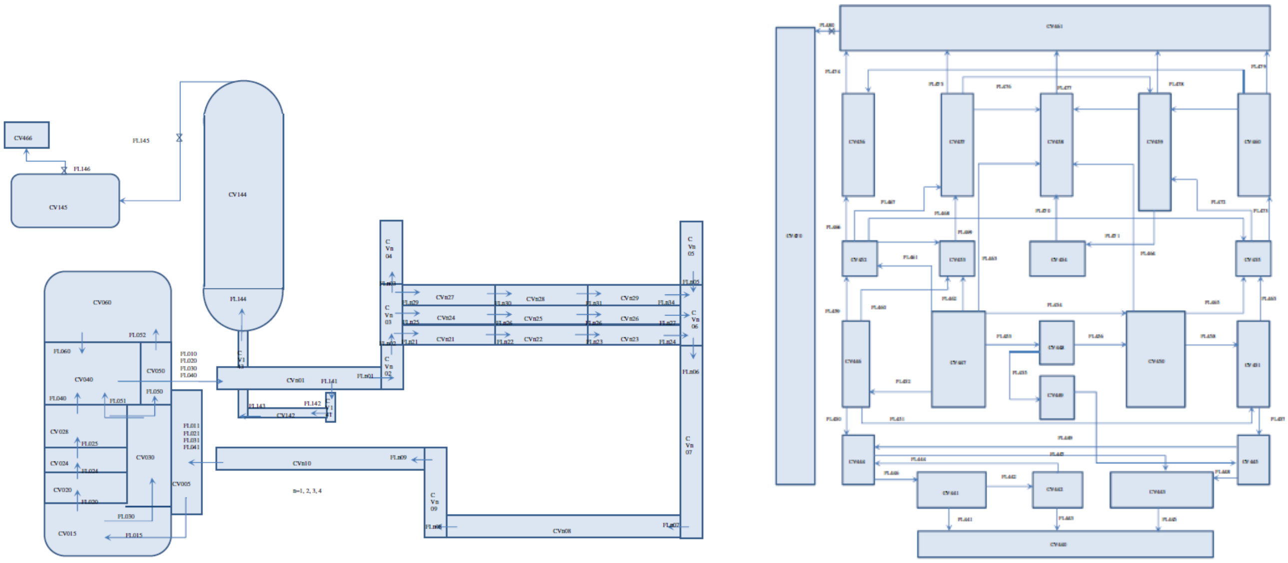

Figure 1. MELCOR containment nodalization scheme for VVER-1000/V320.

- High efficiency and is able to cover a wide range of conditions;
- Consists of fully passive elements and operation;
- Is easy to be installed;
- Is compact and flexible in size;
- Is able to withstand high temperatures.

The exact choice and implementation of a CFVS requires detailed assessment of the requirements and therefore the main goal of this analysis is to investigate the severe accidents conditions and also the specific containment environment relevant for the sizing of the CFVS. The determination of the containment pressurization and the sizing of the filtered venting system are performed based on the analysis of the bounding case of the severe accident scenario that poses the highest requirements to the CFVS.

More specifically the sizing of the containment filtered venting system includes the following main steps:

- Setting up a simulation model and definition of initial conditions;
- Assessment of the boundary conditions for analysis of the parameters during the SA progression;
- Evaluation of the specific characteristics for adequate design of a CFVS.

The target of the calculations is to define performance parameters for the CFVS ensuring that during any SA situation the containment integrity will remain intact for prolonged periods of time.

2 Initial Conditions and Severe Accident Scenario

2.1 Simulation model

In order to support the design and to assess the operation of such CFVS concept, a MELCOR 1.8.5 model of a VVER-1000/320 was developed.

The goal of the MELCOR input development for VVER-1000/V320 is to obtain primary and secondary models, which allows simulation of all of the important phenomena during a severe accident covering the in-vessel and the ex-vessel phases of the accident progression.

The MELCOR nodalization schemes of the primary system and the containment are shown in Figure 1. The model is stabilized at nominal operating conditions.

The initial conditions at which the input deck stabilized corresponding to the plant operational conditions without any conservatism are shown in Table 1 and discussed in the next subsection.

2.2 Initial conditions

A key element of the design of any nuclear power plant to assure safety is the inclusion of multiple barriers to prevent or contain potential release of radioactive materials generated during the fuel fission process.

Accidents in a NPP, leading to core melting are most challenging during full power operational mode. For VVER-1000 among these accidents, large break loss of coolant accident (LB LOCA) scenarios, which lead to early vessel failure and thus to an early predicted containment penetration, are typically assumed for Molten Core Concrete Interaction (MCCI) analyses. In this case additional conservatism is added with respect to high decay power due to the MCCI progression into the basemat [5,6].

One of the factors influencing severe accident progression is the timing of the vessel failure and correspondingly, the time when the pressure in the containment will exceed the design value. In this context, the most challenging for the containment integrity, is the scenario with pressure increase with potential to reached design pressure limit [7].

Therefore as a basis for determination of the design requirement for the CFVS system the following considerations have been chosen:

Table 1. Initial conditions at which the input deck was stabilized correspond to the plant operational conditions

#	Parameter	Typical data	Used for the analysis
1	Reactor thermal power, [MW]	3000±60	3000
2	Core exit pressure, [MPa]	15.79±0.196	15.79
3	SG pressure, [MPa]	6.27±0.19	6.28
4	PRZ pressure, [MPa]	15.7±0.3	15.70
5	RPV inlet temperature, [K]	561.15	562.67
6	RPV exit temperature, [K]	593.15±3.5	593.07
7	SG Feed water temperature, [K]	488.15-498.15±2	493.15
8	Core temperature drop, [K]	30.8±0.5	30.40
9	RPV mass flow rate, [kg/s]	17 610±400	17637
10	Bypass mass flow rate, [%]	3	3.00
11	Pump Heads, [MPa]	0.66±0.0245	0.66

- Containment late over-pressurization;
- LB LOCA with a total loss of the active emergency core cooling system (ECCS);
- Penetration of the steel door between reactor cavity and compartment when the door temperature exceeds the steel failure temperature;

The initial conditions for the chosen scenario are summarized in Table 1.

In such an accident scenario quick dry-out of the core will result in its destruction and melting. Further, the destruction of the core and its relocation at the bottom of the RPV will lead to its failure [8,9]. Hence a faster RPV failure and ejection of debris into the reactor cavity at the highest decay heat is observed. Respectively this will give longer MCCI, and as a result – higher pressure build-up inside the containment.

It should be noted that for VVER operating plants, the design of the containment barrier provides

- Large enough air volume to accommodate the energy released from a design-basis loss-of-coolant accident (LOCA) while not exceeding the design pressure for the containment;
- Systems that include water to absorb the energy released from a LOCA by condensing steam and thereby suppressing the increase in pressure to values below the design pressure for the containment.

The accuracy for predictions of fission product mass concentration in the containment at different stages of an accident is still not very accurate, due to the remaining uncertainties. The ability to model the characteristics of aerosol in the containment has improved significantly over the past few years. The accuracy depends on the plant model, accident sequence and the specific computer code applied.

The results of the calculation of steady state conditions of the unit showed a good convergence with the nominal values of the main parameters on the primary and secondary circuit during normal operation. The results of the MELCOR calculations predict the failure of the vessel for the above mentioned accident. The MELCOR results for the ex-vessel phase of the accident are also obtained.

The implementation of CFVS system and applying proper instructions for human actions by the operators will additionally increase the safety margin in terms of severe accident capability [10,11].

3 Boundary conditions for sizing of CFVS

The aim of the analysis is to define the following input parameters required for design of a CFVS:

- The time of reaching VVER Containment design pressure – 5 bar (absolute);
- The timing of Core Damage, Vessel Failure and melt ejection;
- MCCI progression;
- Generation of steam and non-condensable gases;
- P and T increase;
- Different timing for startup of the filtered venting;
- Atmosphere behavior in containment during accident scenarios;
- Timing of filter start-up and its long term operation in context of severe accident progression;
- Fission products and aerosols in filters;
- Decay heat from radionuclides in filters.

The sizing of the CFVS was performed at two steps – the first step covers evaluation of the scenarios with wet and dry cavity respectively. The second step considers the most realistic case between wet and dry cavities which serves as a base for further calculations. During the second step two cases are studied again by comparison between one and two cavity geometry (potential failure of the door between the cavity and attached compartment).

3.1 Dry versus wet cavity case

For the above described severe accident scenario two cases were calculated - dry case without flooding of the reactor cavity, and wet case with flooding of the reactor cavity. The first scenario is considered more realistic due to the fact that the layout of the reactor cavity does not allow penetration of water as a result of the spray system operation or as a result of other sources of water. The second scenario is chosen since the flooding of the reactor cavity leads to significantly higher steam production and faster containment over-pressurization.

Figure 2 demonstrates the containment pressure histories for the wet and dry cases. In the very beginning, after the LB-LOCA initiation the pressure increases rapidly due the big amount of water-steam mixture which propagates from the primary circuit into the containment. After the primary inventory is discharged the large amount of steam generated starts condensing at the containment

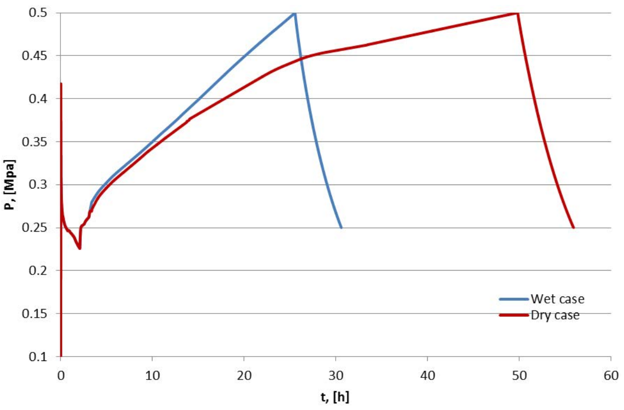

Figure 2. Containment pressure considering dry and wet cavity.

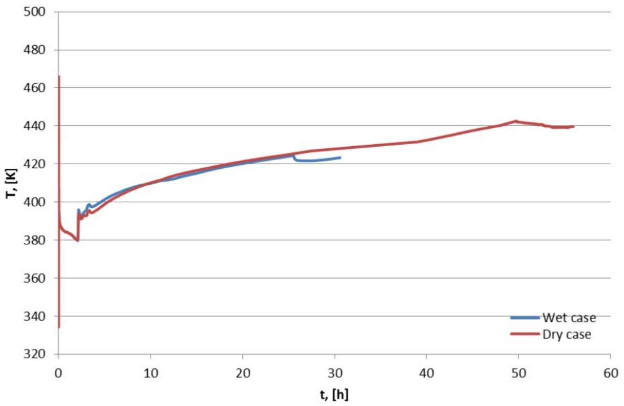

Figure 3. Temperature profiles considering dry and wet cavity.

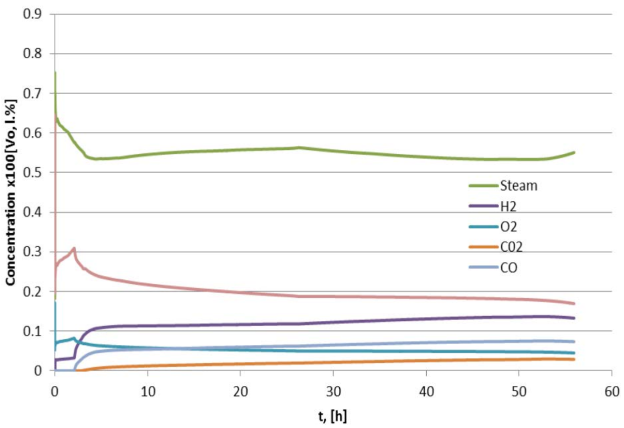

Figure 4. Volumetric concentration of the containment atmosphere components – dry case.

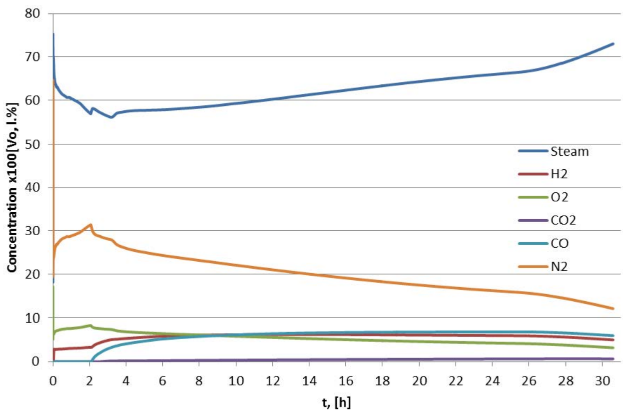

Figure 5. Volumetric concentration of the containment atmosphere components – dry case.

During the ex-vessel phase of the severe accident a big amount of non-condensable gases is generating. The volumetric concentration of the gases in the containment atmosphere is provided in Figure 4.

The partial concentrations of the same gases but for the wet case are provided in Figure 5. As it is expected the steam concentration is much higher than in the case with wet cavity.

The final data of the calculations are summarized in Table 2 and Table 3.

Table 2 considers the parameters of the containment environment at the moment for the containment filtered venting system actuation. Table 3 considers the parameters within the filter resulting from the venting process.

As it was mentioned, the calculations consider two cases – flooded and dry cavity cases. Furthermore, it was assumed that the cavity is flooded and water is supplied to the structures. As a result the containment pressure begins to decrease until the reactor vessel fails and molten material is discharged into the cavity, leading to an increase of pressure inside the containment. After the design pressure is reached the pressure profile is going downward – which reflects the operation of the filtered venting system in the simulation.

The temperature of the containment atmosphere for dry and wet cases is presented in Figure 3. The peak temperature is reached at the moment of initiation of the CFVS – 424 K for wet case and 442 K for the dry case respectively. As can be seen the temperature is increasing constantly until the actuation of the CFVS.

Table 2. Parameters of the environment in the containment at start-up time of CFV system

#	Parameters	Dry case	Wet case
1	Start-up time of CFV system, [h]	52.83	25.50
2	Pressure in the containment at the start-up time of CFV system, [MPa]	0.50	0.50
3	Mass flow of saturated steam at start up time of CFV system, [kg/s]	2.62	2.67
4	Mass flow rate (total), [kg/s]	5.46	5.50
5	Temperature in the containment, [°C]	227.00	151.00
6	Composition of the released gas at the start-up time of CFV system, [Vol.%]		
	H_2	13.86	5.98
	O_2	4.81	4.20
	CO	7.54	6.88
	N_2	18.14	15.82
	CO_2	2.91	0.64
	Steam	52.71	66.48

Table 3. Fusion product characteristics in the filters

#	Parameters	Dry case	Wet case
1	Mass of aerosols in the filter, [kg]	2.92	3.14
2	Mass median diameter of aerosols at start-up of ventilation, [μm]	1.34	1.47
3	Decay heat in the filter (aerosols), [kW]	20.62	32.00
4	Decay heat in the containment at start-up/ end of ventilation, [MW]	10.30/9.95	13.6/12.90

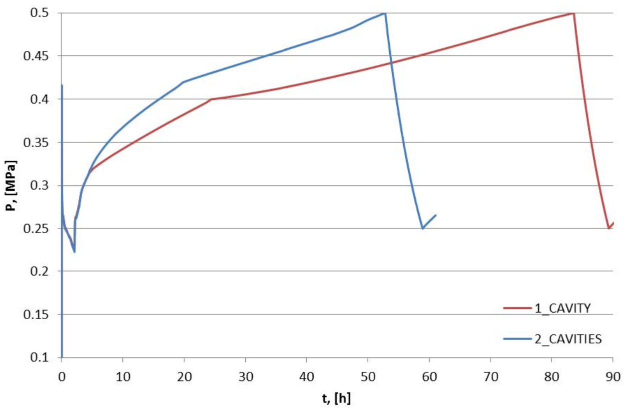

Figure 6. Pressure in one and two cavity geometry.

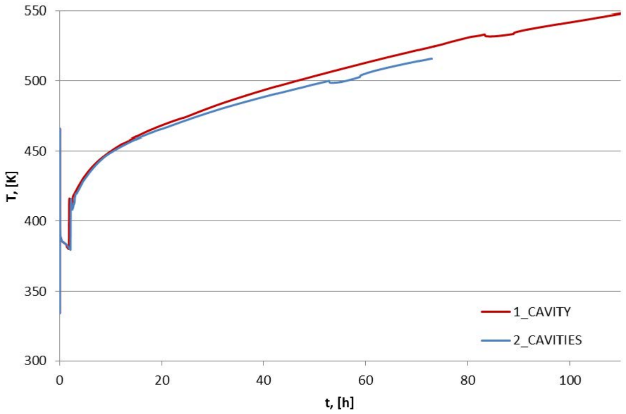

Figure 7. Temperature in one and two cavity geometry.

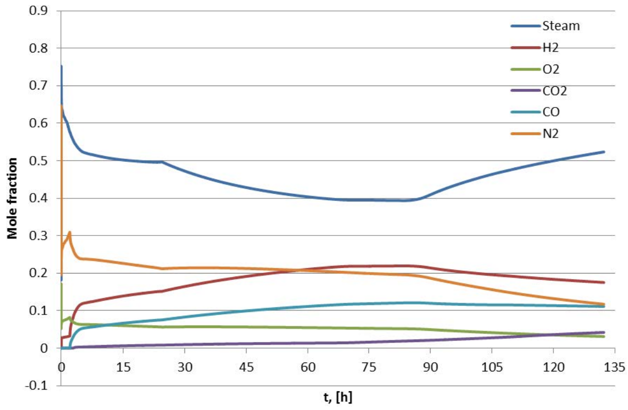

Figure 8. Concentration of the containment atmosphere components – one cavity case.

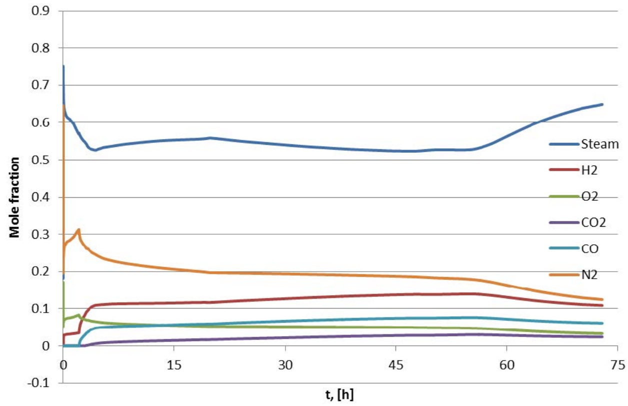

Figure 9. Concentration of the containment atmosphere components – two cavities case.

cavity during the accident progression. The basis for such assumption is potential future modernization efforts allowing for water addition into the cavity.

However such strategy is not adopted yet and still under assessment due to their uncertainties related to the particular design implementation. Therefore the further sizing of the CFVS is performed by assuming only dry cavity as most realistic and applicable case.

3.2 One versus two cavities

The comparison of the results for the containment pressure profiles are demonstrated in Figure 6. The red line represents the containment pressure response in case of one cavity geometry. The containment pressurization continues about 87 hours until the design pressure (5 bars) is reached. In the case with two cavities the pressure increases more rapidly due to the fact that the molten material is in contact with bigger cavity area (after the door failure) and the molten core concrete interaction is more intensive and results in generation of bigger amount of steam and non-condensable gases. After the design pressure is reached the pressure profile is going downward due to the simulated operation of the filtered venting system.

The temperature profiles are shown 1n Figure 7. In case of the one cavity geometry the temperature increases up to 530K at the moment when the design pressure is reached. For the two cavity geometry the maximum temperature is about 480K at the design pressure. Both temperatures are relatively high and set strong requirements with regard to the filtered venting system performance.

The results for the gas composition of the containment environment, in case of one and two cavities, are shown in Figure 8 and Figure 9, respectively.

As a result of the consideration of the one and two cavity scenarios it can be concluded that the two cavity geometry provide more conservative scenario in terms of rapid pressurization and achieving of the containment design pressure.

This conclusion also supports SA mitigation measures implemented at some individual plants, leaving the steel door between the compartments open during operation to minimize the depth of the MCCI in case of a severe accident.

As a result of the performed analysis the following parameters have been defined as a basis for designing an adequate CFVS (Table 4). The table includes results for one and two cavity geometry.

The b and e on the top of each column indicates the beginning and end of each vent respectively.

4 Conclusion

The objective of the analysis, presented here has been the assessment of containment behavior under severe accident conditions after a LB LOCA with loss of active ECCS

Table 4. Parameters of the environment in the containment at begin /end of venting process1 cavity and 2 cavities cases

Cavity, #	**Venting, h**		**T, K**		**Decay heat, MW**		**Mass flow, kg/s**		**H_2 (Ex-vessel), kg**
	b	**e**	**b**	**e**	**b**	**e**	**b**	**e**	
1	83.6	89.3	533.5	533.9	8.9	8.7	4.9	2.4	2841.2
2	52.8	58.9	499.8	502.9	10.3	10.0	5.5	2.7	1831.0

Table 5. Composition of the released gas mixture in containment, 1 cavity and 2 cavities cases

Cavity,#	**Composition of the released gas mixture**											
	Steam		**H_2**		**O_2**		**N_2**		**CO**		**CO_2**	
	b	**e**	**b**	**e**	**b**	**e**	**b**	**e**	**b**	**e**	**b**	**e**
1	39.4	40.6	21.9	21.5	5.2	5.0	19.6	18.8	12.1	12.0	1.9	2.1
2	52.7	55.2	13.9	13.3	4.8	4.5	18.1	16.8	7.6	7.3	2.9	2.9

systems due to SBO to support the design of CFVS for VVER-1000 type NPPs.

The first step of this study was the specification of the severe accident scenario for the VVER-1000. Large break LOCA with a station black-out, which prevents the actuation of the ECCS system and the containment spray, was chosen as scenario with worst consequences for the containment integrity. The containment heat removal systems are also considered not functioning. The only safety system that works is the passive system of hydro accumulators (HA), which discharge water into the vessel at 60 bar pressure.

The next step was to use an appropriate computer code for modeling the phenomenology of severe accidents. MELCOR is one of the most popular computer codes – a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactor nuclear power plants. All countries with operating VVER have been using MELCOR for SA calculations.

The results of the MELCOR simulations predicted the failure of the vessel for the above mentioned accident. The MELCOR results for the ex-vessel phase of the accident were also obtained.

The cavity cannot receive any water from the containment sump and there is (currently) no system to provide any water to the cavity. Nevertheless a case of a coolable configuration of the debris by flooding of the reactor cavity has been analyzed. In this case the containment pressure most rapidly increases and reaches the design pressure (0.5 MPa) earlier.

The analysis also covers the case with only one cavity and the reason is that the cavity is closed to the containment by a massive door of steel, which has been tested to remain closed even with a 0.5 MPa differential pressure. This door remains closed during the accident in this case. As another option is studied failing the steel door between the cavity and compartment and molten corium will spill to the second compartment.

Based on the calculated results it has been justified that the installation of a CFVS will avoid eventual loss of integrity of the containment system due to pressure increase at the late phases of a severe accident progression. The main parameters needed for designs of this system are defined and provided in part 4.

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