

## **Evaluation of Containment Source Term of Various VVER-1000/V-320 Loss of Coolant Accidents**

**Adam Kecek, Lubomír Denk**

ÚJV Řež, a. s.  
Hlavní 130  
250 68 Husinec-Řež, The Czech Republic  
adam.kecek@ujv.cz, lubomir.denk@ujv.cz

**Pavel Král, Hana Hušťáková**

ÚJV Řež, a. s.  
Hlavní 130  
250 68 Husinec-Řež, The Czech Republic  
pavel.kral @ujv.cz, hana.hustakova @ujv.cz

### **ABSTRACT**

Evaluation of containment source term is an essential part of the safety analyses computational chain. This paper deals with containment fission product release during LB LOCA (DBA and DEC A) and SB LOCA (DBA) calculated with COCOSYS computational code. The paper contains a description of the VVER-1000/V320 containment nodalisation for thermal hydraulic and fission product transport calculation as well as a list of the most important initial and boundary conditions. The fission product release from the primary circuit includes both the fission products from fuel and from coolant and follows the principles given by the Czech methodology on fission product release. The evaluation of both accidents, including the thermal hydraulic and fission product transport calculation will be presented. The main scope of this paper is the fission product release through containment leaks as well as through ventilation systems, where both filtered and unfiltered way is considered. The ratio between all investigated ways and the possible impact on the final source term and consequent radiological analyses will be discussed in detail.

### **1 INTRODUCTION**

The containment source term, i.e. the fission product release is the essence of nuclear safety assessment. This release is used in following radiological consequences analyses which estimate whether the legislative limits are met. The containment source term depends on several factors, including containment modelling, initial and boundary conditions as well as the legislative approach. This paper aims to show the difference in the containment source term for various DBA and DEC A scenarios. Furthermore, the release path through ventilation systems and containment leak, including the possible impact on radiological consequences is discussed.

## 2 COMPUTATIONAL CODE AND MODEL

### 2.1 COCOSYS Code

In this study, the COCOSYS 2.4v5 will be used for the analysis of the VVER-1000/V-320 containment behaviour. The COCOSYS code is a lumped-parameter code used for analyses of design basis and severe accident propagation in containments of light water reactors as well as for simulation of experiments. The code itself is based on mechanistic models of relevant physical and chemical processes in LWR containments, i.e. thermal hydraulics and fission product transport. [1]

### 2.2 VVER-1000/V-320 Containment Model

The containment thermal hydraulic nodalisation follows the geometrical subdivision of the containment volume. The philosophy of the nodalisation is to provide a fast-computational model with realistic approach. This is the reason why some rooms were merged into larger nodes. This merging could be done thanks to large openings between the adjacent rooms.

The dominant volume of the containment model is the reactor hall, GA701. The lower half of the containment constitutes of an inner cylinder surrounded by a cylindrical annular cavity. The inner cylinder accommodates the reactor and other important technological equipment, such as steam generators and main coolant pumps. The reactor cavity is subdivided into two separate volumes, GA501 and G301 representing the upper and the lower part respectively. The spent fuel pool is represented by GA401A2 volume. The rooms which accommodate the steam generators are merged into two large volumes, SGBOX-1 and SGBOX-2. Smaller rooms under the steam generator boxes and the reactor cavity are represented by three volumes, the GA306-1, GA306-2 and GA306-3. Under the containment is a L-shaped containment sump, GA201. The cylindrical annular cavity which surrounds the inner cylinder is divided horizontally into two parts, which are further divided vertically into three parts. This yields to CNTU-1 and CNTU-2 representing the upper part, CNTM-1 and CNTM-2 representing the middle part and finally CNTL-1 and CNTL-2 representing the lower part. The total free volume of the containment is approximately 60 000 m<sup>3</sup>. Furthermore, the model contains two large volumes, where BUILDING represents the adjacent buildings and ENVIRON represents the environment surrounding the power plant. Several small nodes model the spray system piping and ventilation systems.

The model further includes heat structures representing the containment walls, floor, ceiling, and other internal structures. Mass flow between the volumes is achieved by junctions which follow the real situation. A special junction is used to simulate the containment leak to the environment, which properties are set to fit the maximum allowed leakages of the containment.

The containment model is further equipped with three separate spray systems. These systems consist of pump, heat exchanger, piping and spray nozzles placed under the reactor hall dome. Delivery and suction ventilation systems maintaining containment underpressure are modelled, where only one of them is filtered. The presence of these systems is essential during the early phase of LOCA accidents because most of the mass released from the containment until approx. 15 seconds (ventilation closure) escapes through ventilation. The filtered ventilation system is equipped with a HEPA (high efficiency particle and aerosol) filter.

COCOSYS demands a separate nodalisation for iodine transport, which can be coarser than the thermal hydraulic one. This means that several thermal hydraulic nodes can be merged into one iodine compartment. To do so, several conditions must comply, e.g. merged nodes must be connected via junctions and the TH conditions must be similar in merged nodes. A graphical interpretation of the nodalisation is in Figure 1. The iodine nodalisation further includes information on surface in each compartment. The user can choose between steel, concrete, and epoxy paint both in gas and water (submerged surface) phase.

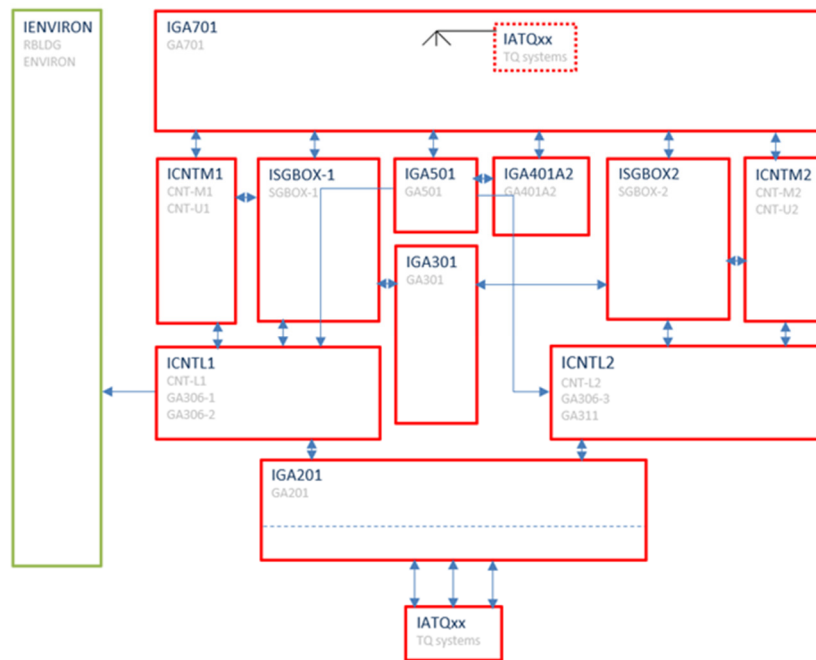


Figure 1 VVER-1000/V-320 containment nodalisation for iodine transport

### 3 ANALYSED ACCIDENTS, INITIAL AND BOUNDARY CONDITIONS

The analyses presented in this paper aim both at the DBA and DEC-A analyses. The main difference is that, in consonance with the current legislative, the DBA accidents follow the conservative approach, and the DEC-A accident should be calculated using the realistic or partially conservative approach [2][3] [4]. The mass and energy release from the primary circuit was calculated with RELAP5/Mod3.3 (DBA LB LOCA and LOCA109) and with ATHLET 3.1 (DEC-A).

#### 3.1 DBA LB LOCA

The initiating event is a guillotine rupture of the loop four cold leg close to the reactor vessel with both sided mass release with equivalent diameter 2x850 mm. Reduced list of the initial and boundary conditions related to the containment behaviour are following:

- Increased reactor power (104 %  $N_{nom}$ ) and decay heat (+15 %)
- Minimal reactor flowrate
- Maximal system temperatures and pressures
- Loss of off-site power at time of the initiating event
- Slow start of diesel generators – maximum delay of initiation of the safety injection (SI) systems

- High and low-pressure injection systems – 1/3 available, hydro accumulators – 2/4 available
- Conservatively low SI pump characteristics
- Maximal water temperature in tanks and piping of safety injection systems
- Minimal water level in tanks of safety injection systems
- Maximal temperature of the heat exchanger cooling water (TQ systems)
- No operator action during the event

### 3.2 DBA SB LOCA

The initiating event is defined as a loss of integrity of the loop four cold leg close to the reactor vessel with one sided mass release with equivalent leak diameter 109 mm. Reduced list of the initial and boundary conditions related to the containment behaviour are following:

- Increased reactor power (104 %  $N_{nom}$ ) and decay heat (+15 %)
- Minimal reactor flowrate
- Maximal system temperatures and pressures
- Loss of off-site power at time of the initiating event
- Slow start of diesel generators – maximum delay of initiation of the safety injection systems
- High and low-pressure injection systems – 1/3 available, hydro accumulators – 2/4 available
- Conservatively low SI pump characteristics
- Maximal water temperature in tanks and piping of safety injection systems
- Minimal water level in tanks of safety injection systems
- Maximal temperature of the heat exchanger cooling water (TQ systems)
- No operator action during the event

### 3.3 DEC-A LB LOCA

The initiating event is a guillotine rupture of the loop four cold leg close to the reactor vessel with both sided mass release with equivalent diameter 2x850 mm. Reduced list of the initial and boundary conditions related to the containment behaviour are following:

- Increased reactor power (104 %  $N_{nom}$ ) and decay heat (+15 %)
- Realistic reactor flowrate
- Realistic system temperatures and pressures
- Loss of off-site power at time of the initiating event
- Slow start of diesel generators – maximum delay of initiation of the safety injection systems
- High and low-pressure injection systems – 1/3 available, hydro accumulators – 2/4 available
- Conservatively low SI pump characteristics
- Maximal water temperature in tanks and piping of safety injection systems
- Minimal water level in tanks of safety injection systems
- Maximal temperature of the heat exchanger cooling water (TQ systems)
- No containment spray system in operation
- No operator action during the event

### 3.4 Fission Products

The fission products (FP) available for the containment calculation come from two main sources. The first is the primary coolant, where fission products origin from untight fuel pins and from the corrosion products. The second source is from fuel pins dehermetized during the accident. No fuel deterioration is expected. The released inventory follows the R.G. 1.183 [5] basic principles with some modifications concerning the number of failed fuel rods [6]. Summary of these releases is presented in Table 1.

Table 1: In-containment source term for various LOCA accidents

| Accident      | FPs from primary circuit                                                                                                                                              | FPs from fuel                                                                                                                                                                                                                                              |
|---------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| DBA SB LOCA   | 100 % of the FP inventory, 3.8 % directly to the atmosphere, the rest goes to water, 0 – 13 s,<br>Iodine – 95 % CsI, 4.85 % I <sub>2</sub> , 0.15 % CH <sub>3</sub> I | Failure of 10 % of the fuel pins, release of 5 % of the failed rod inventory (Cs, Rb, Br, I, Kr, Xe)<br>Release directly to the atmosphere, 30 – 1800 s after the initiating event<br>Iodine – 95 % CsI, 4.85 % I <sub>2</sub> , 0.15 % CH <sub>3</sub> I  |
| DBA LB LOCA   | 100 % of the FP inventory, 4.1 % directly to the atmosphere, the rest goes to water, 0 – 12 s,<br>Iodine – 95 % CsI, 4.85 % I <sub>2</sub> , 0.15 % CH <sub>3</sub> I | Failure of 100 % of the fuel pins, release of 5 % of the failed rod inventory (Cs, Rb, Br, I, Kr, Xe)<br>Release directly to the atmosphere, 30 – 1800 s after the initiating event<br>Iodine – 95 % CsI, 4.85 % I <sub>2</sub> , 0.15 % CH <sub>3</sub> I |
| DEC-A LB LOCA | 100 % of the FP inventory, 4.5 % directly to the atmosphere, the rest goes to water, 0 – 14 s,<br>Iodine – 95 % CsI, 4.85 % I <sub>2</sub> , 0.15 % CH <sub>3</sub> I | Failure of 33 % of the fuel pins, release of 5 % of the failed rod inventory (Cs, Rb, Br, I, Kr, Xe)<br>Release directly to the atmosphere, 30 – 1800 s after the initiating event<br>Iodine – 95 % CsI, 4.85 % I <sub>2</sub> , 0.15 % CH <sub>3</sub> I  |

## 4 RESULTS AND DISCUSSION

The evaluation is aimed at release of iodine which is a dominant fission product in the evaluation of radiological consequences. The released mass is presented in relation to the DBA LB LOCA, which was chosen to be the reference calculation.

### 4.1 Containment thermal hydraulics

The only relevant acceptance criteria for VVER-1000/V-320 containment in the Czech Republic is the maximum overpressure, which is 400 kPa. The investigated accidents proved to be below this limit.

The containment pressure evolution is different for each scenario. The DBA LOCA109 exhibits slow pressurization, forming the first peak around 700 s. Later, the pressure starts to decrease slowly due to the containment spraying, cf. Figure 2.

The DBA LB LOCA exhibits rapid pressurisation reaching the peak around 15 s followed by a depressurisation. Around 1000 s a secondary pressure peak is formed. The pressure then drops due to the containment spraying, cf. Figure 2.

The DEC-A LOCA exhibits similar behaviour in the early phase with a significant primary pressure peak followed by a smaller secondary pressure peak. Unlike the DBA scenario, the slow depressurisation ends around 5 000 s and the containment pressure rises due to the malfunction of the spray systems, cf. Figure 2.

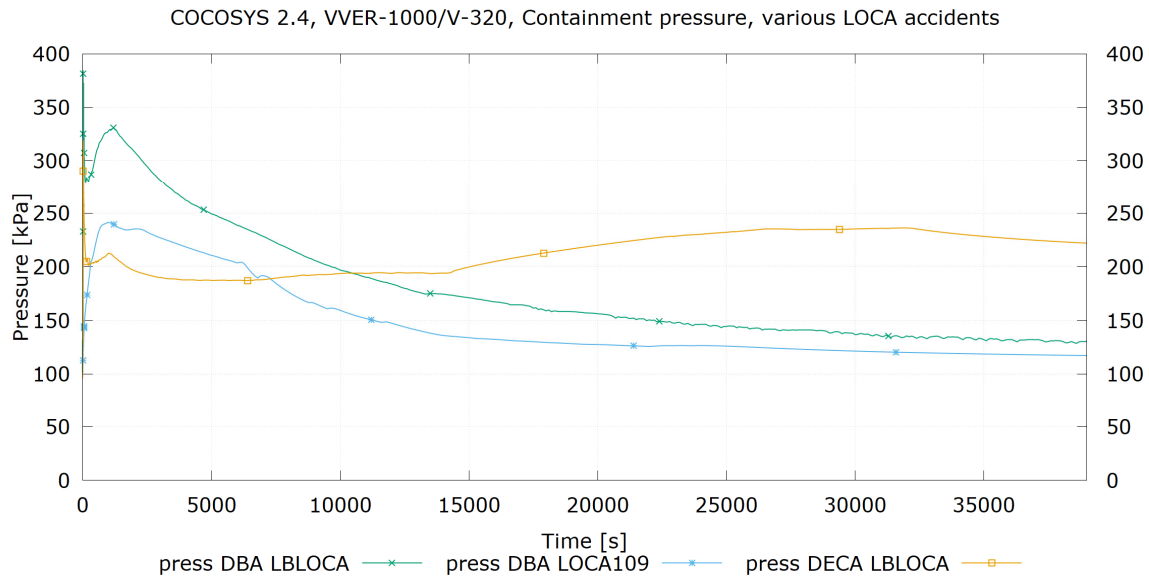


Figure 2 Containment pressure evolution (VVER-1000/V-320, various LOCA accidents, 0 - 39 000 s)

## 4.2 Containment leak release

The iodine mass release shows similar behaviour for DBA LB LOCA and LOCA109. The released mass does not follow the initial ratio of containment inventory (1:10). The released mass is approximately three times lower for the LOCA109. Such differences may be caused by a different process of containment pressurization and mass transfer in the containment volume. The DEC-A LOCA exhibits slower decrease of the release rate. Even though the initial inventory is three times lower compared to the DBA LB LOCA, the released iodine mass is slightly higher. This may be caused by the malfunction of the spray system, cf. Figure 3.

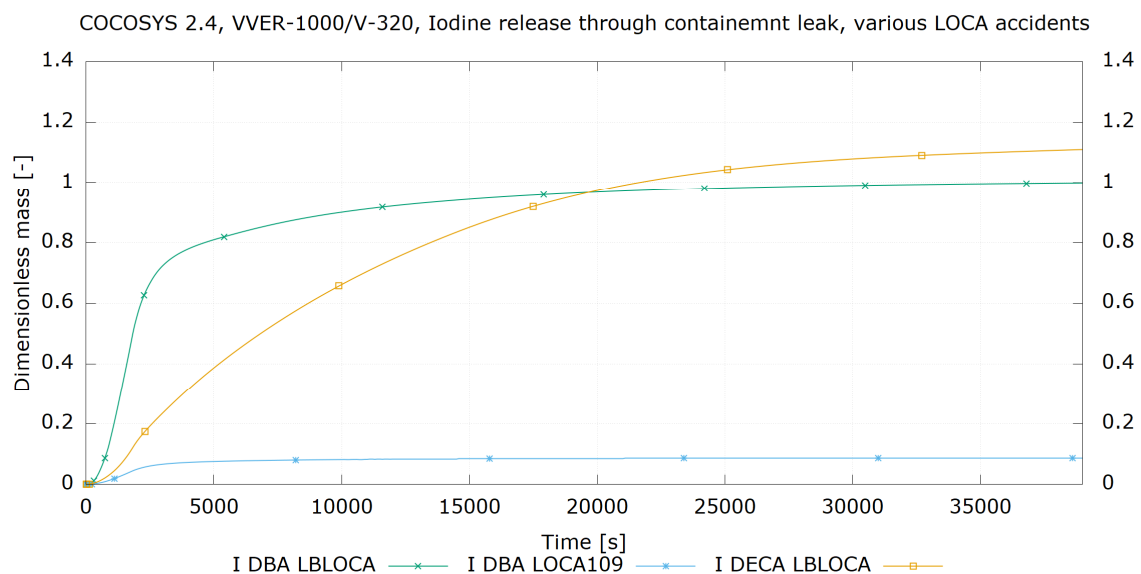


Figure 3 Iodine relative mass release through containment leak (VVER-1000/V-320, various LOCA accidents, 0 – 39 000 s)

### 4.3 Ventilation system release

The ventilation system release is governed mainly by the containment pressurization, which is slowest for the DBA LOCA109 and fastest for the DBA LB LOCA. The release through the TL22 system, in comparison to the TL42, is almost negligible due to the presence of the fission product filter. The released mass can be observed in Figure 4.

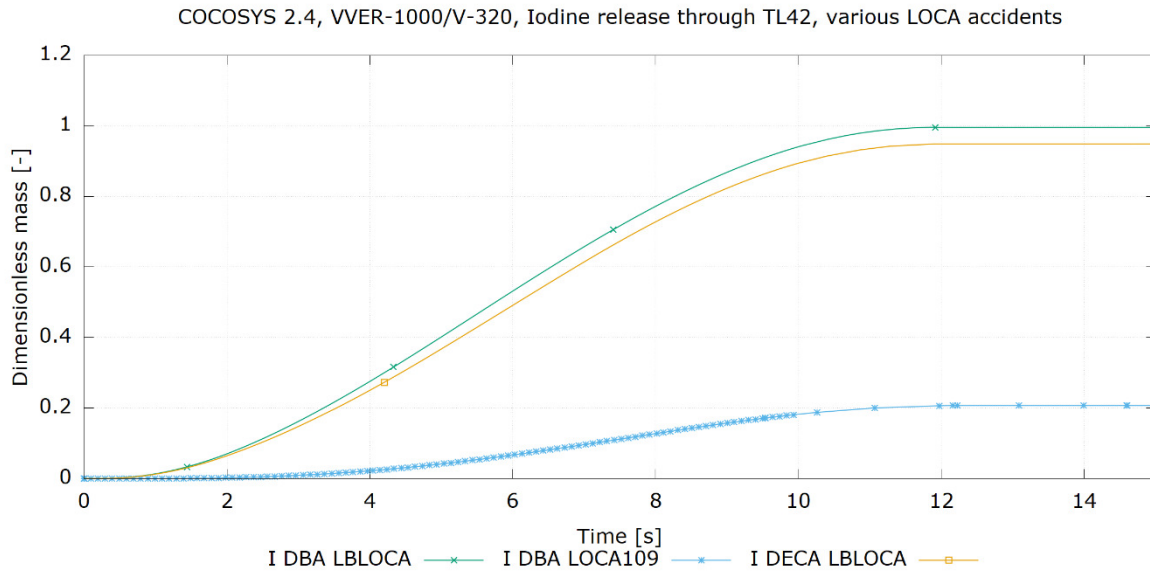


Figure 4 Iodine relative mass release through TL42 ventilation system (VVER-1000/V-320, various LOCA accidents, 0 – 15 s)

### 4.4 Comparison of released fission product mass for DBA LB LOCA

The ratio between investigated leak paths, i.e. the filtered and unfiltered ventilation and containment leak is presented in Table 2. At 15 s, the majority is released through the unfiltered ventilation. At the end of the calculation, the situation is different, the majority is released through the containment leak. This could be expected because the ventilation systems are closed since 12 s approximately.

Table 2: Ratio of each path release for DBA LB LOCA

|                               | 15s [%] | 39 000 s [%] |
|-------------------------------|---------|--------------|
| TL22 (filtered ventilation)   | 0.002   | Negligible   |
| TL42 (unfiltered ventilation) | 99.898  | 0.2          |
| Containment leak              | 0.100   | 99.8         |

## 5 SUMMARY

The containment source term, i.e. the fission product release, is the essence of nuclear safety. The scenarios analysed in this paper revealed that the released mass is governed by various initial and boundary conditions including, e.g. the containment fission product initial

inventory or availability of spray systems. The spray systems proved to be an important technical equipment for mitigation of release of fission products, namely the iodine.

The fission product mass release through the containment leak proved to be the dominant way of fission product release into the environment. Unfortunately, for further radiological consequence analyses, the fission product mass released to the environment is not the only important initial and boundary condition. These calculations require the information on isotopic composition of the source term as well, e.g. the iodine released in the early phase is mainly composed of long lived isotopes whereas the iodine released from fuel has a significant fraction of short lived isotopes. This may, in some cases, yield to significantly stronger impact of the early releases to the total calculated radiological consequence, because the calculated mass release from the containment does not take this effect into account. The release through ventilation systems may be even more important for specific DEC scenarios such as LOCA with containment bypass.

## REFERENCES

- [1] W. Klein-Heßling, S. Arndt, H. Nowack, C. Spengler, S. Schwarz, D. Eschricht, S. Beck, *COCOSYS V2.4v5 User's Manual*, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) gGmbH, Cologne, Germany (2018)
- [2] *Bezpečnostní návod BN-JB-2.10 (Rev. 0.0) Deterministické bezpečnostní analýzy událostí abnormálního provozu a základních projektových nehod*, State Office for Nuclear Safety, Prague, Czechia (2020)
- [3] *Bezpečnostní návod BN-JB-2.2 (Rev. 0.0) Deterministické analýzy rozšířených projektových podmínek bez vážného poškození paliva DEC A*, State Office for Nuclear Safety, Prague, Czechia (2019)
- [4] P. Kral: *Evolution and Implementation of the Design Extension Conditions (DEC) Concept*, Assessment of Selected Events, ICON 26, 2018
- [5] US NRC, *Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors*, R.G. 1.183, United States Nuclear Regulatory Commission, USA (2000)
- [6] L. Denk: *Metodika výpočtů radiačních následků pro bezpečnostní zprávu*, ÚJV Z5085 T, ÚJV Řež, a. s., 2018