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Uncertainty and sensitivity evaluation of aerosol deposition in PHEBUS containment during FPT-2 experiment

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During a hypothetical severe accident at a nuclear power plant (NPP), the aerosols and radionuclides could be released from the reactor through the engineering systems to the surrounding atmosphere. The last barrier preventing release is the containment, which surrounds the reactor and the main engineering systems. Most of radioactivity is released in the form of particles (aerosols). Therefore, aerosol transport and deposition processes are very important for NPP safety. Description of these processes requires a lot of physical parameters and conditions. Naturally, these parameters bring their own uncertainties, and so uncertainty and sensitivity analyses are necessary for final assessment of the accuracy of results.

This paper presents the uncertainty and sensitivity analysis of PHEBUS FPT-2 simulation performed with the SUSA software. The containment simulation results were received using the lumped-parameter code COCOSYS. This paper includes a description of the PHEBUS containment, nodalisation, initial and boundary conditions, results and conclusions. The uncertainty analysis was performed assuming 95/95 probability, and tolerance limits showed that the measured values of the aerosol mass suspended in the gas phase were within the calculated uncertainty limits. However, the deposition on the vertical containment walls is not within the calculated limits. The sensitivity analysis showed that the parameters having the largest influence on the investigated parameters (mass suspended in gas phase, deposition on containment elliptic floor, deposition on condensers, deposition on vertical walls) are the following: the Mass Median Diameter (MMD), the dynamic shape factor, the particle agglomeration factor, the water film thickness, the initial pressure, the Geometric Standard Deviation of particle diameter, and the thickness of diffusive boundary layer.

Key words: nuclear power plant, containment, uncertainty and sensitivity analysis

INTRODUCTION

At present, the best-estimate approach is usually used for safety assessment of the Nuclear Power Plants. This method includes not only the usage of the best-estimate computer code and best-estimate assumptions, but it also requires assessment of uncertainties. The best-estimate plus uncertainty approach is more and more often used for the thermal-hydraulic analysis of loss-of-coolant events. In general, the aim of the uncertainty analysis is at first to identify and quantify all potentially important uncertain parameters.

In the FPT-2 final report [1], it is described that "in practice, the uncertainty of a result may arise from many possible sources, including environmental conditions, uncertainties of initial inventories and sampled volumes, approximations and assumptions incorporated in the measurement method, and random variations. In estimating an overall uncertainty, it may be necessary to take each source of uncertainty and treat it separately to obtain its contribution".

The computer code predictions are uncertain due to several sources of uncertainty, e. g. code models, uncertainties of power plant parameters. The models in computer codes are developed based on measured results during different tests representing complex behavior of NPP under accident conditions in a simplified way only. The scaling effect of the performed experiments is also an issue. The parameters of the power plants are always changing, and it is impossible to know exactly the combination of all acting parameters, evaluation of which should be performed.

One of the main issues using lumped-parameter codes is the development of nodalisation. This issue is already investigated, and nodalisation development is described in detail in [2]. The application of the best-estimate nodalisation for analysis of fission product transport is presented in [3]. The second important issue for correct simulation of transport and deposition processes of aerosol and fission products is thermal-hydraulic phenomena. The calculated thermal-hydraulic results are in good agreement with those measured and are described in detail in paper [3].

Some parametric analyses have already been performed to investigate the influence of particle solubility and density parameters on aerosol deposition and distribution in the PHEBUS FPT-1 experiment [4] and diffusive deposition in FPT-2 [5]. Paper [6] describes the results of FPT-2 analysis using ASTEC1.1, CONTAIN and MELCOR codes and includes the sensitivity assessment for particle size, shape and density, which helps to define the limits of uncertainty parameters. According to the mentioned paper, a very high dynamic shape factor ($\chi = 3$, $\chi = 6$) seems to be unrealistic, because the particles are too far away from the spherical form, and the dynamic shape factor varies in the range around 1. In [7] it is shown that the computer code ASTEC/CPA underpredicts the deposition by diffusiophoresis on the wet condensers, and it hardly foresees, like all codes, any deposition on the containment wall. The summary of PHEBUS FPT-0, FPT-1 and FPT-2 containment phenomena investigation using ASTEC/CPA has also been recently published in [8].

In the above-mentioned papers, the effects of modeling parameters are investigated in a parametric way, i. e. changing one parameter, while the other parameters are assumed constant. Therefore, it remains unknown whether the selected parameters are giving the largest influence on the uncertainty of results, and what kind of influence could be expected from the other parameters. A more detailed and integrated assessment is needed to better define the most important parameters. One of the methodologies for the assessment of the uncertainties and sensitivity of results on different modeling parameters is the GRS methodology described in [9]. This methodology is based on statistical methods that stand with stochastic evaluation and propose results in a sensible form, it evaluates input data, their adjustment and mathematical handling influence on final results and is used in the computer code SUSA [10], which is developed by GRS mbH (Germany). Although in 2011 an uncertainty analysis of FPT-2 test was performed, but this analysis included only those parameters that relate to the aerosol and fission product module (AFP) of COCOSYS code [2].

This paper presents the uncertainty and sensitivity analysis of the PHEBUS FPT-2 test assessment for aerosol transport and deposition in the containment. This analysis takes into account uncertainty not only of parameters related to particle transport but also of thermal-hydraulic parameters. The containment processes were investigated using the computer code COCOSYS [11], while the uncertainty and sensitivity analysis was performed using the computer code SUSA [10]. Both the tolerance limit and the confidence level were set to 0.95 for the analysis. According to the Wilks formula, the minimum number of calculations for two-sided statistical tolerance limits is 93 to define the number of runs needed for at least 95% probability content and at least 95% confidence. To satisfy this requirement of the minimum number of calculation, 100 runs were performed using the COCOSYS code in case some calculations were faulty.

In this paper, the uncertainty and sensitivity are assessed not only for aerosol deposition rate but also for the aerosol deposition distribution as well. The results of the performed analysis revealed the most significant parameters for aerosol deposition on different surfaces in the FPT-2 test. These are the Mass Median Diameter (MMD), the dynamic shape factor, the particle agglomeration factor, the water film thickness, the initial pressure, the Geometric Standard Deviation, and the diffusive boundary layer thickness.

DESCRIPTION OF EXPERIMENT FPT-2

The PHEBUS containment vessel is a 10 m^3 tank (see Fig. 1a), made of electro-polished stainless steel (AISI 316L), in which aerosols and gases conveyed through the experimental circuit during the test are collected [1]. The nodalization scheme of the PHEBUS containment model for the COCOSYS code is shown in Fig. 1b. The height of the containment is 5 m with an inner diameter of 1.8 m. The containment has a cylindrical form with a rounded bottom and a top. The outer vessel walls were heated to avoid steam condensation and subsequent aerosol deposition on the containment top vault and vertical walls

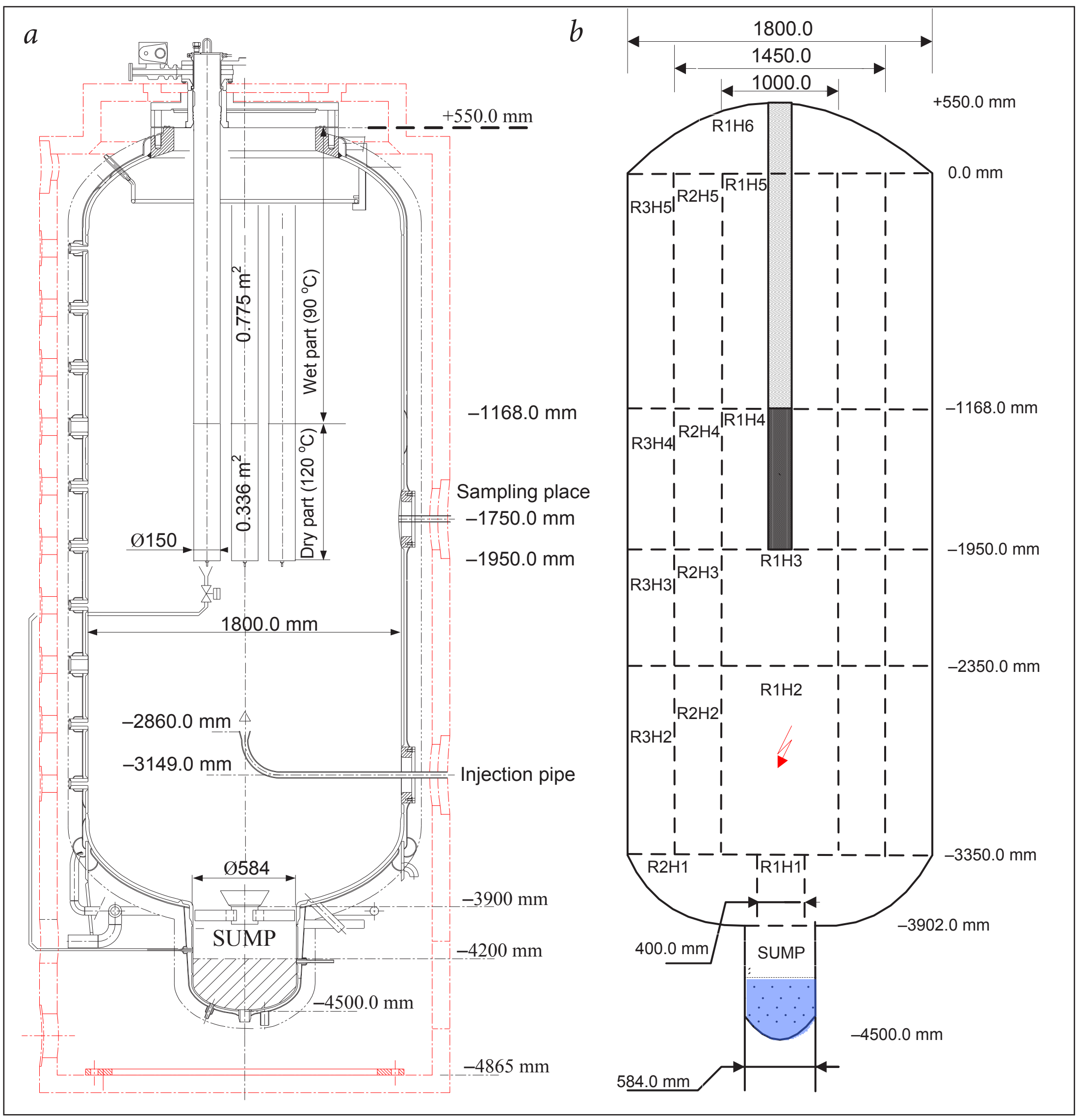

Fig. 1. PHEBUS containment schematic view (*a*) [1] and nodalization scheme (*b*)

during the test. The top vault is equipped with a group of three condensers, which are designed to control the heat transfer and steam condensation, and, thus, simulates the cold structures of a reactor building. The sump is a lower vessel part closed by a curved bottom structure with a volume of 0.1 m^3. The sump was initially filled with 0.11 m^3 of water. The injection pipe tag to the containment of steam, hydrogen and aerosols is located at –2.86 m. The pipe tag is in the centre of the containment and points at the condensers. A more detailed description of the PHEBUS containment geometric conditions is presented in [3].

During the test preparation phase, nitrogen was injected into the containment to avoid any explosion hazards with the possible hydrogen injection during the experiment. As a result, the initial pressure in the containment increased to 1.95 bar; the average atmosphere temperature was 108 °C, and the average relative humidity was 51.48%. The composition of the containment atmosphere consisted of condensable gases (i. e. steam) and non-condensable gases (i. e. H_2, O_2, N_2 and He). During the entire test period, the temperature of containment walls in contact with the gas phase was 110 °C; the temperature of the "wet" condensers was 90 °C, the temperature of the "dry" condensers was 120 °C, and the temperature of walls in contact with the sump was 90 °C. The containment vessel boundary conditions were chosen to limit the relative humidity to from about ~50 up to ~70% during the transient in order to prevent steam condensation on the external containment walls. Steam condensation in the containment was controlled by the cooled condensing surfaces of the condensers.

Measured steam and hydrogen flow rates into the containment are shown in Fig. 2. Aerosol injection started after ~9 000 s and the release continued until ~19 500 s (see Fig. 3). The total injected mass of aerosols was 44.69 g. The measured particle geometric mean diameter was 0.45 μm, with the geometric standard deviation 1.78.

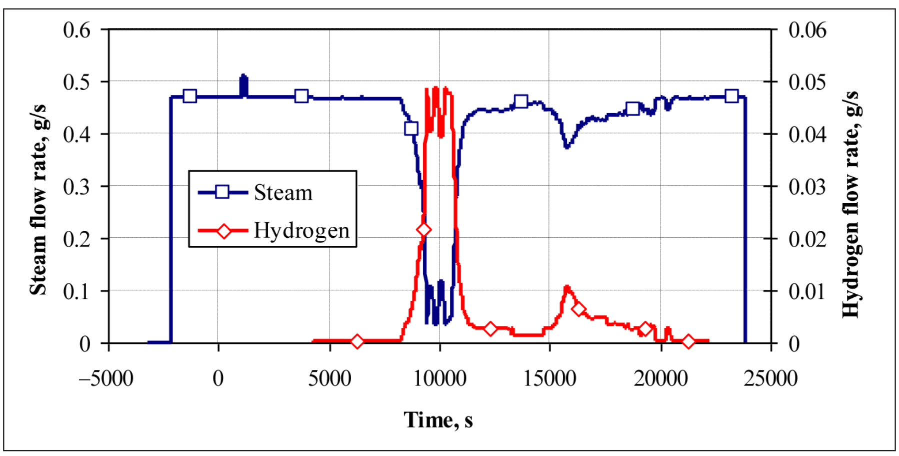

Fig. 2. Steam and hydrogen flow rates to containment during FPT-2 [1]

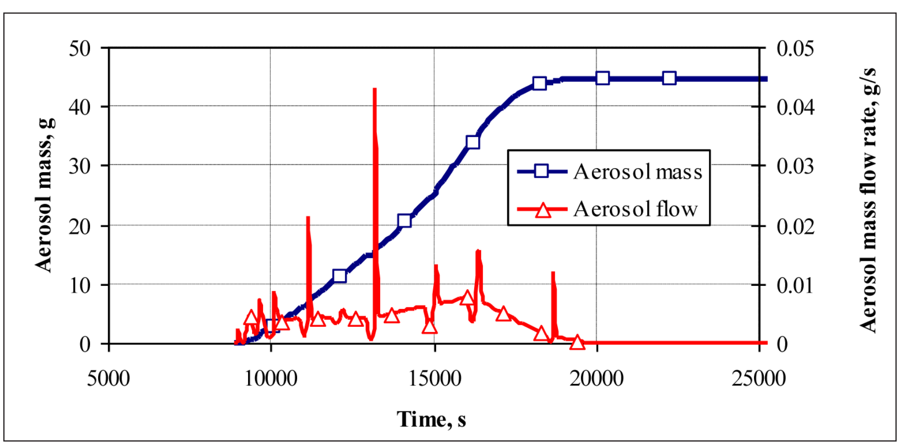

Fig. 3. Injected aerosol mass and flow rate to containment during FPT-2 [1]

MODEL OF PHEBUS CONTAINMENT

For simulation of the aerosol and fission product transport in the PHEBUS containment, a model of 16 nodes for the COCOSYS code was developed. The nodalization scheme of the model is shown in Fig. 1b. In the model, the radial subdivision of the containment consisted of two rings in the close level above the sump. There was the centre node R1H1 and node R2H1 that simulated the bottom part of the vessel. Above –3 350 mm and below 0 mm levels, there were three almost equal area rings. The diameter of the radial subdivision was defined in such way that the flow areas were similar. Such approach to nodalization gave similar flow velocities. A ring close to the external containment walls was 175 mm width. At the top vault of the vessel, there was one additional node. Simulation at the top vault by a single node gave the well-mixed conditions at the top of facility. A similar approach was used at the bottom of the facility. Above the SUMP nodes were defined in such way that there were two junctions to the SUMP. Such approach ensures better mixing and allows avoiding the dead-end node, which is not recommended for lumped parameter codes [12].

Eleven structures for the simulation of heat transfer through the containment walls to the outer atmosphere were defined in the model. Two more structures were defined for the simulation of heat transfer between the condensers and the inner atmosphere.

All PHEBUS containment surfaces and condensers were made of stainless steel. Only the surface of the condensers was covered with epoxy paint to investigate chemical interactions of iodine with the paint [8].

Atmospheric junctions with real geometric areas for the simulation of gas flows between the nodes were defined. In [8] a special definition of the gas flow resistance close to the walls was suggested. However, such approach was not used here, and no special definition of changing flow resistance was given, i. e. all junctions have the same resistance coefficient, which changes in all junctions simultaneously for uncertainty assessment. Also, junctions for the simulation of water drainage from the "wet" condenser to the sump were defined.

In the developed model, the initial and boundary conditions (e. g. initial pressure, temperature, humidity, etc.) were defined according to the FPT-2 test Final Report described in Section 2 [1]. In the developed input deck, it is assumed that the aerosol diameters range between 10^{-8} and 10^{-4} m, and they have log-normal distribution described by 20 size classes. The base case estimated aerosol density assumed 3 000 kg/m^3.

In the analysis, it was assumed that the aerosols could be deposited on different surfaces by the following mechanisms: gravity driving aerosols towards the containment bottom, diffusiophoresis driving the aerosols towards the "wet" condensers, aerosol diffusive deposition on the containment vertical walls. The thermophoresis is neglected, as there are no hot surfaces in the FPT-2 test that would have effect on the results.

Taking into account that during this test the relative humidity is not exceeding 80%, it is assumed that steam condensation on the aerosols is not expected. However, the aerosols that are deposited on the "wet" condensers could be washed down by the condensate flow. The aerosols slip through the vertical junctions is considered.

The aerosols were assumed to be spherical. The composition of elements detected in the containment was given in the FPT-2 test Final Report [1]. It is assumed that the solubility factors are 1.0 and 1.73 for non-soluble and soluble elements, respectively.

RESULTS OF THE ANALYSIS

Table 1 presents the list of 24 parameters included in the performed uncertainty and sensitivity analysis. The table includes the expected or base case values and the assumed range of values. The first 15 parameters are related to the particle transport modeling in the AFP module of COCOSYS code, the rest 9 parameters are related to the thermal-hydraulic analysis. All the base case values are taken either according to the FPT-2 test Final Report [1] or available experience simulating the thermal-hydraulic and aerosol transport analysis of PHEBUS FPT-1, FPT-2 and FPT-3 tests.

The base case aerosol density (parameter No. 5) was not measured during the test. Used values are from 3 000 to 7 000 kg/m^3 [13] or even 500 kg/m^3 for comparison purposes [6]. The mass median

Table 1. **Parameters of uncertainty and sensitivity analysis**

No.	Parameter	Base case value	Min. value	Max. value	Standard deviation (σ value)
1.	Solubility factor of soluble aerosols	1.73	1.45	2.0	0.1375
2.	Dynamic shape factor	1.0	0.84	1.16	0.08
3.	Particle sticking probability factor	1.0	0.84	1.16	0.08
4.	Particle agglomeration factor	1.0	0.84	1.16	0.08
5.	Aerosol density, kg/m^3	3 000	2 520	3 480	2 40.0
6.	Mass median diameter, m	$2.02 \cdot 10^{-6}$	$1.69 \cdot 10^{-6}$	$2.34 \cdot 10^{-6}$	$1.63 \cdot 10^{-6}$
7.	Geometric standard deviation	2.0	1.68	2.32	0.16
8.	Number of aerosol size classes	20	17	20	0.75
9.	Molecular weight of soluble component, g/mol	118	99.12	136.8	9.42
10.	Molecular weight of non-soluble component, g/mol	114	95.76	132.24	9.12
11.	Diffusive boundary layer thickness, m	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$
12.	Particle slip coefficient	1.37	1.15	1.58	0.1075
13.	Average thickness of water film, m	$3.0 \cdot 10^{-4}$	$2.52 \cdot 10^{-4}$	$3.48 \cdot 10^{-4}$	$0.248 \cdot 10^{-4}$
14.	Molecular weight of gas, g/mol	20.35	17.0	23.0	1.5
15.	Turbulence dissipation rate, m^2/s^3	0.02	0.0168	0.0232	0.0016
16.	Initial average temperature, °C	108.0	107.0	109.0	0.5
17.	Initial relative humidity, %	51.29	50.29	52.29	0.5
18.	Initial pressure, bar	1.95	1.85	2.05	0.05
19.	Loss coefficient for atmospheric junctions	1.5	1.0	2.0	0.25
20.	Water volume in sump, l	120.0	110.0	130.0	5
21.	Temperature of sump walls, °C	90.0	89.0	91.0	0.5
22.	Temperature of containment walls, °C	110.0	109.0	111.0	0.5
23.	Temperature of "wet" condensers, °C	90.0	89.0	91.0	0.5
24.	Temperature of "dry" condensers, °C	120.0	119.0	121.0	0.5

diameter (parameter No. 6) is calculated taking into account the measured aerodynamic mass median diameter [1] and the assumed aerosol density. In the COCOSYS input deck, two parameters have to be defined: 1) Mass Median Diameter (MMD) and 2) aerosol density [12]. During the FPT-2 test, the Aerodynamic Mass Median Diameter (AMMD) was measured, which can be expressed as [12]

$$\mathrm{AMMD} = \mathrm{MMD}\sqrt{\rho / (\rho_w \cdot \chi)},$$

where δ is the aerosol density, δ_w is the density of water (1 000 kg/m^3), and χ is the dynamic shape factor. MMD and AMMD are similar parameters, which are obtained experimentally by using an impactor, which was calibrated using spherical particles of unit density. If a particle of a given shape and density impacts to the same place as a 1 μm spherical particle of unit density, then it is said that both particles have the same AMMD and behave aerodynamically identically. In the performed uncertainty analysis, there was intention to maintain the same AMMD as it was measured during the test, i. e. changing aerosol density consequently changes the MMD according to the presented formula.

The diffusive boundary layer thickness (parameter No. 11) was selected according to the COCOSYS manual recommendations [12] and confirmed by the theory described in [14].

The loss coefficient for atmospheric junctions (parameter No. 19) was selected according to available experience simulating thermal-hydraulic and aerosol transport analysis of PHEBUS tests.

The base case values of thermal-hydraulic parameters for the uncertainty analysis were taken according to the FPT-2 test Final Report [1].

The uncertainty range of all parameters related to aerosol modeling (parameters No. 1–15) is assumed ±16% according to the FPT-2 Final Report [1]. In the COCOSYS code, the number of particle size classes (parameter No. 8) has to be integer value – maximum of 20 size classes. The minimum value is calculated according to the assumed uncertainty range. The uncertainty range for temperatures is assumed ±1 °C according to the specification of thermocouples. The uncertainty of relative humidity is ~±2%, the initial average pressure ±0.1 bar, and the volume of water in the sump is ±10 l.

It is assumed that all parameters are distributed within the defined range according to the Normal (Gaussian) distribution.

Figure 4 shows the results of the uncertainty analysis for the aerosol mass suspended in the gas phase. The maximum, minimum, average and median values are compared with the test results. The measured results are within the calculated uncertainty band. When the peak value is reached, the measured results are closer to the average calculated value, but then it decreases faster, and later it complies with the minimum calculated values. This result shows that the COCOSYS code can simulate the main particle transport and sedimentation processes.

The Spearman's rank correlation coefficient is used to estimate the sensitivity of results to uncertain parameters. The Spearman's coefficient shows how well two variables are monotonically related. In the performed analysis, the calculated determination coefficient R^2 for all 24 parameters varied between 0.95 and 0.99; thus, the Spearman's rank correlation coefficient could be used for the sensitivity analysis.

Figure 5 shows 4 parameters giving the largest influence (Spearman's coefficient larger than ±0.3 at least in one point) on the results: the dynamic shape factor (parameter No. 2), the particle agglomeration factor (parameter No. 4),

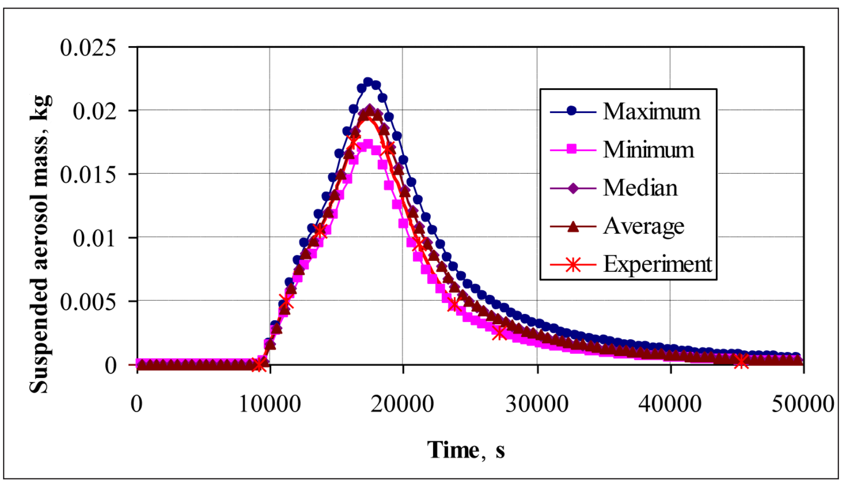

Fig. 4. Suspended aerosol mass (maximum, minimum, median, average and experiment values) in containment

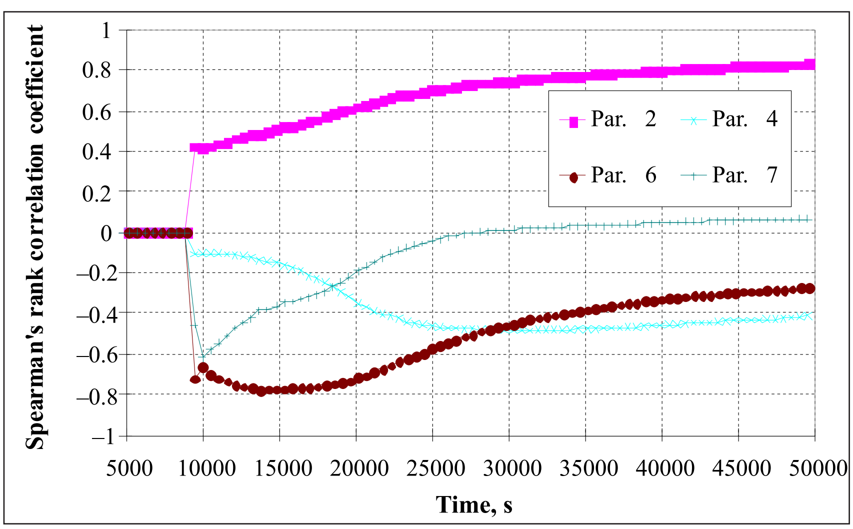

Fig. 5. Spearman's rank correlation coefficients for suspended aerosol mass (only the parameters with coefficient exceeding 0.3 at least at one point are highlighted)

the Mass Median Diameter (parameter No. 6) and the geometric standard deviation (parameter No. 7). The dynamic shape factor has a positive influence on the results, i. e. increasing its value (more deviation from spherical shape) leads to higher aerosol mass suspended in the containment atmosphere. Increasing the MMD or the particle agglomeration factor leads to faster deposition of particles on the internal surfaces and less mass suspended in the atmosphere.

Figure 6 presents ranking of the coefficients shown in Fig. 5. Before 22 000 s, the largest influence was from the MMD (parameter No. 6), which directly influences the particle deposition. After 22 000 s, the influence of the dynamic shape factor (parameter No. 2) increases together with the particle agglomeration factor (parameter No. 4) because the form and size of particles have strongly changed in comparison to the initial parameters. MMD influence decreases because most of particles had agglomerated and initial particle properties became less important. The geometric standard deviation (parameter No. 7) had a greater influence only in the beginning of aerosol injection and the reason is particle agglomeration and loss of initial properties during the test. In the long term, this parameter has only a minor influence (ranking 18–24 out of 24 selected parameters).

In Fig. 7, the parameters that had the greatest influence on aerosol deposition on the containment floor are presented. Only the parameters

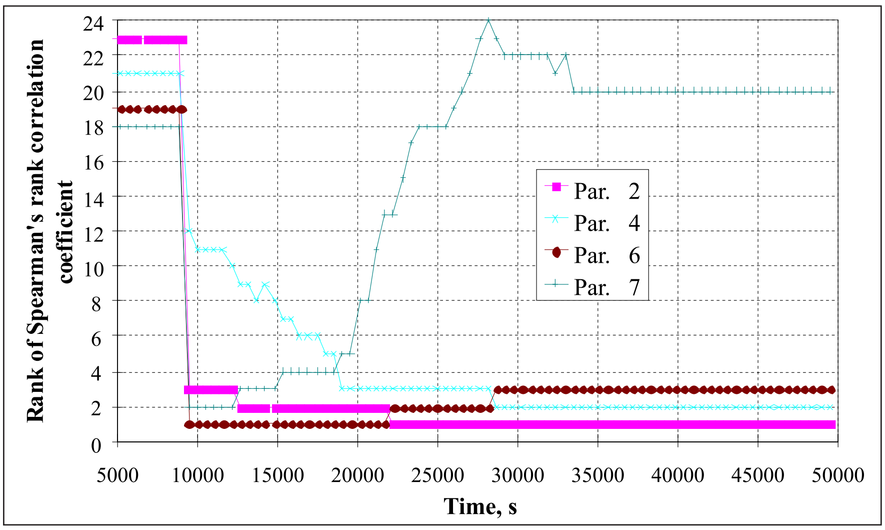

Fig. 6. Rank of Spearman's rank correlation coefficients for suspended aerosol mass

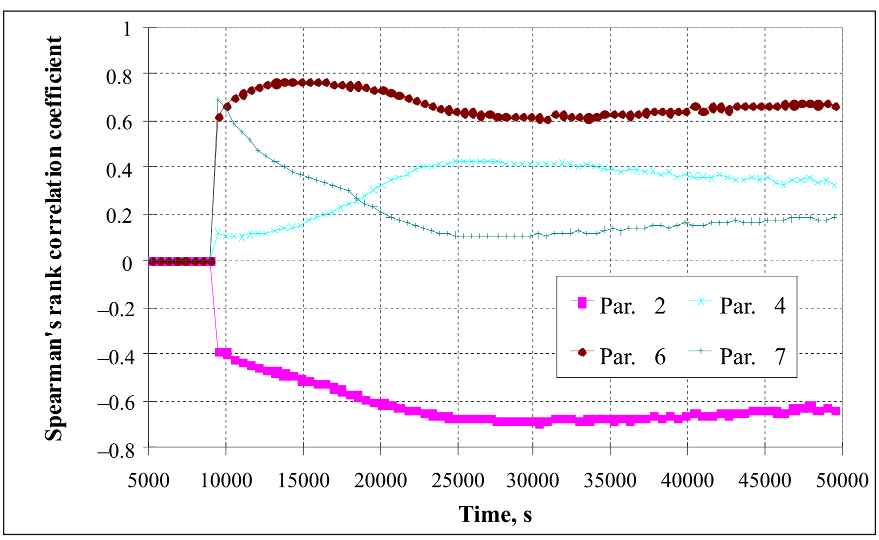

Fig. 7. Spearman's rank correlation coefficients for aerosol deposition on containment floor

with the Spearman's rank correlation coefficient exceeding 0.3 at least at one point are highlighted. These parameters were the same as those for aerosol mass suspended in the containment atmosphere: the dynamic shape factor (parameter No. 2), the particle agglomeration factor (parameter No. 4), the mass median diameter (parameter No. 6) and the geometric standard deviation (parameter No. 7). Compared to the results shown in Fig. 5, one could see that the influence of parameters on the deposition on the floor is opposite, e. g. the increasing dynamic shape factor (increasing deviation from the spherical particle) leads to less deposition on the floor. Increasing the MMD and particle agglomeration factor leads to the increased deposition due to gravitational settling.

The rank of Spearman's correlation coefficients for aerosol deposition on the containment floor of the 4 most important parameters is presented in Fig. 8. In this case, the dynamic shape factor, the particle agglomeration factor and MMD are top 3 during the entire analysed test period. The geometric standard deviation does not fall below importance level 12, while for the suspended aerosol mass, it had the lowest ranking.

In Fig. 9, the parameters that had the greatest influence on aerosol deposition on the condensers

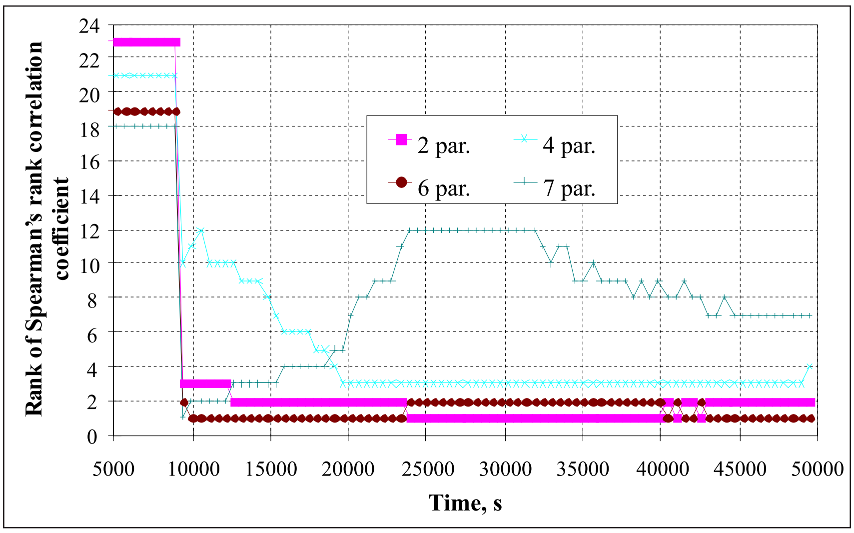

Fig. 8. Rank of Spearman's rank correlation coefficients for aerosol deposition on containment floor

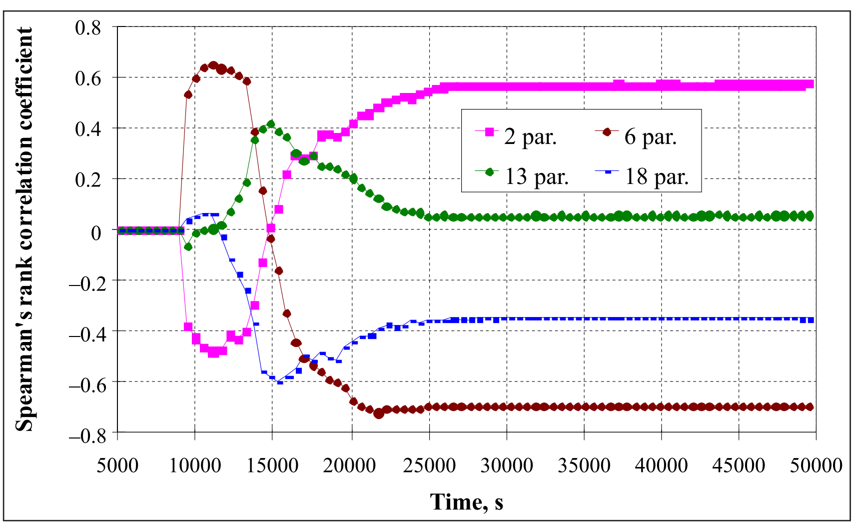

Fig. 9. Spearman's rank correlation coefficients for aerosol deposition on the condensers and in the sump

and in the sump are presented. Only the parameters with the Spearman's rank correlation coefficient exceeding 0.3 at least at one point are highlighted.

The dynamic shape factor (parameter No. 2), the MMD (parameter No. 6), the average thickness of water film (parameter No. 13) and the initial pressure (parameter No. 18) were the most important parameters for deposition on the condensers and in the sump. In the beginning of aerosol injection, the increasing dynamic shape factor leads to less deposition on the condensers; however, later the influence changes the direction, and deviation from the spherical shape leads to more deposition on the condensers. This could be explained by saying that in the beginning of aerosol injection, the particles interact more close to the injection point, and there is a small number of particles close to the condensers. When the particles reach the "wet" condensers, they tend to deposit there since the residence time of non-spherical particles in the gas phase is longer. A similar explanation could be given to the influence of MMD – in the beginning of aerosol injection, more particles are transported by the gas flow up to the condensers, and they deposit there, but later larger particles deposit faster due to gravitational settling, and then they reach the condensers. The water film thickness affects the drainage of water from the "wet" condensers to the sump, thus, affecting wash-down of the aerosols as well. The initial pressure in the containment defines the amount of non-condensible gases, and this parameter has impact on the aerosol deposition on the condensers.

Diffusive deposition on the containment walls is the most important for particles with the diameter <0.1 μm [15]. Figure 10 presents the parameters, which had the greatest influence on aerosol deposition on the containment walls and were removed by sampling. The most important parameters were the geometric standard deviation (parameter No. 7) and the thickness of the diffusive boundary layer (parameter No. 11). All the other parameters have the Spearman's rank correlation coefficient less than 0.3. As in other cases, the geometric standard deviation is important only in the beginning of aerosol injection, and later its importance diminishes. Thus, the only important parameter, which in the developed COCOSYS input deck defines aerosol deposition on the vertical walls, is the diffusive boundary layer thickness; the correlation coefficient during the calculated period is almost 1. The smaller the thickness of the diffusive boundary layer is, the more particles deposit on the vertical walls. However, there is no theoretical substantiation for the diffusive boundary layer reduction below 10^{-4} m, and even according to [14], it is recommended to use the diffusive boundary layer in the range between 10^{-3}–10^{-4} m and to avoid too small values.

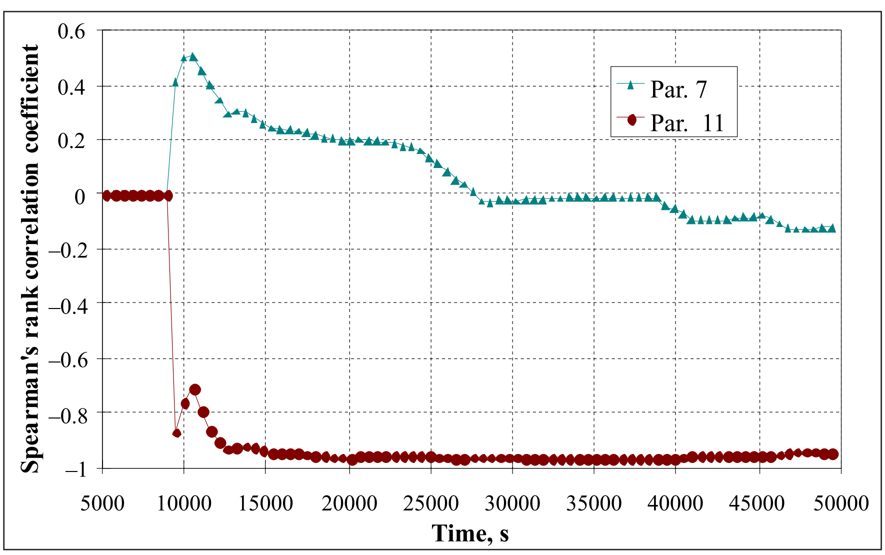

Fig. 10. Spearman's rank correlation coefficients for aerosol deposition on the containment walls and sampling (only the parameters with coefficient exceeding 0.3 at least at one point are highlighted)

The distribution of aerosol deposition on different surfaces in the containment is shown in Table 2. The largest deposition of aerosols was measured on the containment floor around the sump, where 74% of aerosols were deposited. Besides, it was measured that 14% of aerosol mass was deposited on the condensers and in the sump, and 12% was deposited on the vertical containment walls and removed by sampling. The performed uncertainty analysis showed that the measured deposition on the elliptic floor and on the condensers was within the calculated range of the results; however, deposition on the containment vertical walls is far from the calculated results; the maximum value is only 0.9%. This result implies that the model for diffusive aerosol deposition included in the COCOSYS code needs updating.

Table 2. **Distribution of aerosol deposition**

	Floor of containment	Condenser surfaces and sump	Containment walls + samplings
Measured	74.0%	14.0%	12.0%
Min	71.44%	11.28%	0.42%
Max	86.88%	27.66%	0.9%

CONCLUSIONS

The uncertainty and sensitivity analysis of processes that occurred in the PHEBUS containment during the FPT-2 test was performed using the SUSA software. The COCOSYS code was used for the analysis of processes in the PHEBUS containment.

The obtained results were compared with experimental values, and the following conclusions were formulated:

1. The performed uncertainty analysis showed that the measured aerosol mass suspended in the gas phase of the containment lay within the calculated uncertainty range.

2. The performed sensitivity analysis highlighted parameters, which had the largest influence on:

• aerosol mass suspended in the gas phase – dynamic shape factor, particle agglomeration factor, mass median diameter and geometric standard deviation;

• aerosol deposition on the containment floor – dynamic shape factor, particle agglomeration factor, mass median diameter and geometric standard deviation;

• aerosol deposition on the condenser surfaces and in the sump – dynamic shape factor, particle agglomeration factor, water film thickness and initial pressure;

• aerosol deposition on containment walls – geometric standard deviation and diffusive boundary layer thickness.

3. The calculated deposition distribution on various surfaces in the containment showed that deposition on the elliptic floor and on the condensers are within the uncertainty range of calculated results; however, the calculated deposition on the vertical walls (0.4–0.9%) is far from measured 12%. It implies that a diffusive deposition model included in the COCOSYS code should be revised and further investigation dedicated to diffusive deposition analysis with more preferable model determination should be performed.

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AEROZOLIŲ NUSĖDIMO PHEBUS APSAUGINIAME KIAUTE FPT-2 EKSPERIMENTO METU NEAPIBRĖŽTUMO IR JAUTRUMO ANALIZĖ

Santrauka

Branduolinių jėgainių eksploatacija yra susijusi su rizika, kad įvykus avarijai radioaktyviosios medžiagos, susidarančios branduoliniame kure, gali pasklisti už jėgainės ribų, todėl yra įrengiami apsauginiai barjerai, ribojantys radioaktyviųjų medžiagų sklaidą. Apsauginis kiautas, gaubiantis reaktorių, aušinimo kontūrą ir kitas saugai svarbias sistemas, yra paskutinis barjeras, ribojantis radioaktyviųjų medžiagų sklaidą ir neleidžiantis joms patekti už jėgainės ribų. Vis dėlto aerozolių ir radionuklidų pernešimo ir nusėdimo procesų įvertinimas yra svarbus saugiai branduolinės jėgainės eksploatacijai. Šiems procesams įvertinti yra būtina ištirti daug fizikinių parametrų ir eksploatacijos sąlygų. Suprantama, kad kiekvienas parametras turi savas paklaidas, todėl neapibrėžtumo ir jautrumo analizė yra reikalinga įvertinant skaičiavimo rezultatų tikslumą.

Šiame straipsnyje pateikta PHEBUS FPT-2 eksperimento tyrimo neapibrėžtumo ir jautrumo analizė, atlikta naudojant SUSA programų paketą. Skaitinio tyrimo rezultatai gauti naudojant suvidurkintų parametrų programų paketą COCOSYS. Šiame darbe aprašytas PHEBUS apsauginis kiautas, jo skaitinis modelis COCOSYS programų paketui, pradinės ir kraštinės įvykdyto eksperimento sąlygos, gauti rezultatai ir išvados. Skaitiniam tyrimui atlikti pateikti 24 parametrai, aprašyti rezultatų skyriaus pradžioje. Neapibrėžtumo analizė atlikta 95/95 tikimybės ir tolerancijos intervalu parodė, kad išmatuota dujinėje terpėje esančių aerozolių masė patenka į skaičiavimų neapibrėžtumo ribas. Tačiau išmatuota dalelių masė, nusėdusi ant vertikalių apsauginio kiauto sienelių, nepatenka į skaičiavimo ribas. Jautrumo analizė parodė, kad didžiausią įtaką nagrinėtiems rezultatams 1) dujinėje terpėje esančių aerozolių masė; 2) aerozolių masė, nusėdusi apatinėje apsauginio kiauto dalyje; 3) aerozolių masė, nusėdusi ant kondensatorių; 4) aerozolių masė, nusėdusi ant vertikalių apsauginio kiauto sienelių) turi: vidutinis dalelės skersmuo, dalelės formos dinaminis veiksnys, dalelių aglomeracijos koeficientas, kondensato plėvelės storis, pradinis slėgis apsauginiame kiaute, dalelės skersmens geometrinis standartinis nuokrypis ir difuzinio pasienio sluoksnio storis.

Raktažodžiai: branduolinė jėgainė, apsauginis kiautas, neapibrėžčių ir jautrumo analizė