DEALING WITH UNCERTAINTIES IN NUCLEAR SAFETY ANALYSES – PART II (DETERMINISTIC APPROACH)

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Lucrarea este structurată în două părți: (I) tratarea incertitudinilor în abordarea probabilistă; (II) tratarea incertitudinilor în abordarea deterministă.

Partea I a prezentat contribuțiile autorilor la dezvoltarea metodologiei analizei de incertitudine din studiul probabilist (PSA) de evaluare a securității nucleare.

Partea a IIa prezintă contribuții originale în estimarea incertitudinilor şi influența lor în rezultatul final pentru abordarea deterministă. A fost aleasă o situație foarte complexă: transportului produşilor de fisiune în circuitul primar CANDU, în timpul unui accident sever. Pentru cei mai senzitivi parametri au fost selectate domenii de variație credibile şi valori ale parametrilor care respectă distribuțiile postulate. Este realizată şi o analiză a influențelor acestor parametri în cele mai importante date de ieşire.

The paper is structured in two parts: (I) uncertainties treatment for probabilistic approach; (II) uncertainties treatment for deterministic approach.

Part I presented the contribution of the authors to the development of the methodology for uncertainty analysis in probabilistic safety assessments calculations.

Part II presents some original contributions for the uncertainties estimations and their influences in final results for a deterministic approach. A very complex situation is chosen: fission products transport in CANDU primary circuit during a severe accident. For the most sensitive parameters, credible domains of variations were selected and values of the parameters respecting postulated distributions. An analysis of the influences of these parameters in the most important output results is performed.

Keywords: severe accidents, fission products, Monte Carlo, uncertainty analysis

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1. Introduction

Consideration of Severe Accidents (SAs) represents an essential aspect of defence in depth concept used in nuclear safety of NPPs. SAs are accident conditions more severe than Design Basic Accidents (DBAs), have very low probabilities and could have significant consequences resulting from nuclear fuel degradation [1].

Many phenomena as fuel failure, FPs transport in Primary Heat Transport (PHT) system and containment system, core melting, corium formation and relocation, core-concrete interaction, etc. ask for a deep knowledge and understanding. Also, the interaction between these phenomena, their modelling by using computer codes, the experimental data used to validate the codes, the user experience are essential items in performing SAs analysis. Important uncertainties are embedded in all this aspects, and can affect the results of any SA analysis. There are three major sources of uncertainty in accident analyses [2]: code or model uncertainty; representation or simulation uncertainty; and plant uncertainty.

Another potential source of uncertainty which can introduce variability in the results of SAs analysis is the user effect. This is connected with user expertise, quality and comprehensiveness of the code user manual, the availability of database in performing the analysis, etc. [3].

To understand how the reactor and its containment respond under SAs conditions, computer codes simulations are used. An important knowledge obtained by experiments was included in the codes. Many phenomena dedicated codes and some integral codes (calculates the entire sequence of a SA) were developed in the world. An important integral code developed for light water reactor from the initiating event (IE) up to the FPs releasing into the environment, covering all important in-vessel and ex-vessel phenomena, is ASTEC [4]. Important efforts are performed in Europe in order to harmonize the methodologies regarding SAs, such as in the Severe Accident Research Network of excellence (SARNET). On this basis ASTEC became the reference European integral code for SA reactor safety in generation II&III PWR-VVER [5]. Some efforts are in progress in order to extend the ASTEC use to all European reactors (including CANDU, RBMK and BWR).

For CANDU type reactors, the use of ASTEC introduces many difficulties, especially concerning the core degradation phenomena [4]. However, some modules of the code can be successfully used to simulate important SAs phenomena such as FPs transport in PHT system and containment, FPs chemistry, thermal hydraulics, etc. The studies performed under SARNET FP6 project have demonstrated that SOPHAEROS module can be fully used at CANDU type reactors.

Below, some contributions of the authors in dealing with uncertainties in the FPs deposition and transport in the CANDU PHT system during a severe accident are presented. They refer to model uncertainty, the user effect and uncertainty analysis in order to obtain the trusting domain of the output variables. All the analyzed situations use SOPHAEROS module in stand alone mode. It calculates the FPs deposition and transport through the heat transport system components and piping and provides the amount of FPs retained in the PHT system and the release transients into the containment [1]. The postulated severe accident is initiated by a Loss of Coolant Accident (LOCA) + Loss of Emergency Core Cooling (LOECC) + Loss of Moderator (LOM).

2. Model uncertainty

2.1. The influence of feeders diameters on the masses of FPs deposited in CANDU PHT system

The code or model uncertainty represents uncertainty associated with the code models and correlations, the solution scheme, model options, unmodelled processes, data libraries, deficiency of the computer program and simplifying assumption and approximation.

The CANDU PHT geometry is quite complicated: two loops arranged in a figure-of-eight configuration with the coolant making two passes in opposite directions through the core during each complete circuit. From this reason the exact treatment of the geometry, is difficult enough. One of the PHT CANDU complexities is given by the existence of 5 classes of feeders according to diameter. In table 1 the diameter of feeders for the five classes of diameters (D_1, D_2, D_3, D_4 and D_5), is presented [6].

Table 1

Classes of diameters for feeders

Class of diameters of feeders	D_1	D_2	D_3	D_4	D_5
Diameter [mm]	85.4	73.4	59	49.3	38
Radius [mm]	42.7	36.7	29.5	24.65	19

A simplified geometry for PHT is considered in order to calculate the FPs deposited masses (Fig. 1.). It is based on averaged diameters for horizontal and vertical feeders and simplified circuit.

Therefore, ¼ CANDU simplified PHT circuit, consists of 95 horizontal fuel channels (Fuel Channel – node 1) connected to 95 horizontal out-feeders (OFeeder2 – node 2), then through vertical feeders (OFeeder3 – node 3) to the outlet-header (a big pipe which collects the water from feeders); the circuit continues from the outlet-header (Header – node 4) with a riser (Riser – node 5) and then with the steam generator (STG1 – node 6, STG2 – node 7, STG3 – node 8) and a pump (InPump – node 9, Pump – node 10, OutPump – node 11). After this pump, the circuit was broken; at this point the FPs are transferred to the containment.

For each of the five classes of feeders stand alone mode runs of SOPHAEROS module (version included in ASTEC V1.3) were performed.

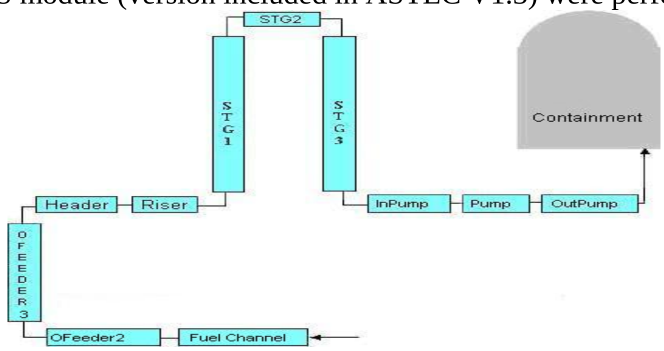

Fig. 1. Simplified ¼ CANDU primary circuit

Margin and initial conditions (such as pressure and temperature evolutions) were supplied based on external codes' results (CATHENA for thermal hydraulics conditions, ORIGEN for FPs inventory). FPs deposited masses have been obtained firstly, considering single feeder's class [7]. Then by a weighted mean corrected deposited mass for each FP and the corrected total masses for these FPs have been obtained, as can be seen in table 2 [7].

The corrected total masses (last column in Table 2) have been obtained as:

$$m_j = \frac{1}{N_{tot}} \sum_{i=1}^{5} N_{D_i} (m_{D_i})_j \qquad (1)$$

where:

m_j = the total corrected mass of the fission product j (j = I, Xe, ... , Pd, Te);

N_{TOT} = the total number of feeders from the modelled primary circuit;

N_{D_i} = the numbers of feeders from the class of feeders having the diameter D_i;

$(m_{D_i})_j$ = the stored mass of the fission product j, for the class of feeders having the diameter D_i.

Table 2

FPs deposited masses in PHT circuit for each of the 5 classes of diameters of feeders

FP	The corrected masses of FPs for each class, obtained by SOPHAEROS calculation [kg]					PHT total deposited mass [kg]
	D_1	D_2	D_3	D_4	D_5	
I	0.110276	0.110635	0.112905	0.116011	0.11864	0.568467
Xe	0	0	0	0	0	0

Cs	0.107388	0.107107	0.109075	0.111605	0.113291	0.548465
Ba	0.082955	0.083322	0.085711	0.088834	0.091499	0.432321
La	0.051741	0.051852	0.05279	0.05406	0.055054	0.265498
Ce	0.138056	0.13835	0.140855	0.144244	0.146896	0.708401
Pr	0.006726	0.006747	0.006862	0.007027	0.007164	0.034526
Nd	0.018204	0.018243	0.018573	0.01902	0.01937	0.09341
Pm	0.001517	0.001522	0.001553	0.001596	0.00163	0.007819
Sm	0.002436	0.002444	0.002494	0.002562	0.002617	0.012553
Kr	0	0	0	0	0	0
Rb	0.001904	0.001904	0.001839	0.001839	0.001773	0.009258
Sr	0.063463	0.063674	0.065431	0.06775	0.069647	0.329965
Y	0.028048	0.028108	0.028586	0.029273	0.02981	0.143824
Zr	0.028852	0.028914	0.029471	0.030213	0.030831	0.148281
Mo	0.102725	0.102943	0.104577	0.106864	0.108716	0.525824
Tc	0.004052	0.004065	0.004134	0.004229	0.004311	0.020792
Ru	0.084646	0.084826	0.086264	0.088151	0.089678	0.433565
Pd	0.001865	0.001869	0.001903	0.001946	0.001984	0.009566
Te	0.122167	0.122558	0.124777	0.127779	0.130128	0.62741

In previous calculations $N_{D1} = N_{D2} = N_{D3} = N_{D4} = N_{D5} = 19$ it was supposed.

The analysis presented here, shows that the influence of model uncertainty is very important, having relevant effects in the final results. By the proposed method (weighted mean), the model uncertainty derived from the inadequacy between the real geometry of CANDU PHT and SOPHAEROS model geometry introduced by using an average diameter for feeders, can be partially solved.

2.2. The influence of uncertain parameters on the FPs deposition and transfer to the containment

The influence of the uncertainty introduced by the differences between the real geometry of CANDU PHT system and SOPHAEROS model geometry (Fig. 1.) mainly introduced by the feeders' description is treated in the following. The influences on the most important output parameters (the FPs masses deposited into PHT, FPs masses transferred to the containment) for Caesium, Strontium and Iodine are presented.

The horizontal and vertical feeders are represented in SOPHAEROS module (from ASTEC V1.3) by diameter and length averaged feeder. This fact introduces uncertainties on final results. In order to reduce the uncertainties, interpolation approach based on Taylor expansion has been developed [8]. Its aim is to calculate the masses deposited for different individual feeders and finally the total FPs PHT deposition and transfer to the containment, for a real geometry structure of feeders.

Thus, SOPHAEROS multiple calculations for different averaged feeders have been performed and the interpolation method based on Taylor formula has been used. The following steps have been done [8] as:

1. Individual calculations for each of five classes of feeder diameters (Table 1) and constant length;
2. Individual calculations for different lengths of the horizontal feeders in the interval [4.1, 6.0]m;
3. Polynomial fitting to obtain analytic dependences of the FPs deposited masses on the feeders' diameter and length;
4. Derivative calculations of the obtained mathematical function to obtain the coefficients of Taylor expansion formula;
5. Calculation of FPs deposition and transfer for different dimensions (lengths and diameters) by direct SOPHAEROS calculations and by using Taylor expansion formula;
6. Comparison of the previous step results to prove the validity of the approach and the limitations;
7. Estimation of the FPs deposition and transfer for a defined geometry structure by using a weighted formula.

The dependence of Cs mass on the horizontal feeders' length for 5 radius classes (Table 1) is presented in Fig. 2. An approximately linear dependence can be observed. Despite of this, the dependence on the feeders' length is quite non-linear (Fig. 3).

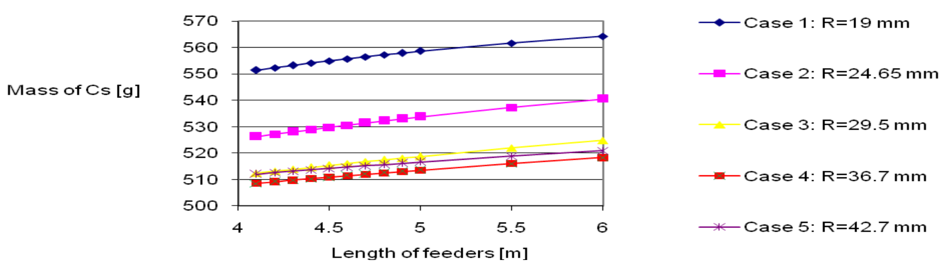

Fig. 2. The dependence of Cs mass on the horizontal feeders' length for 5 radius classes

Taking into consideration the previous mentioned variables (x_1 = horizontal feeder's radius; x_2 = horizontal feeder's length) by Taylor expansion the value for an individual feeder is:

$$f(x_1, x_2) = f(x_{10}, x_{20}) + \frac{\partial f}{\partial x_1}(x_1 - x_{10}) + \frac{\partial f}{\partial x_2}(x_2 - x_{20}) + O(2) \qquad (2)$$

where:

- (x_{10}, x_{20}) are the calculation points used in steps 1 and 2 of the approach;
- (x_1, x_2) are the expansion points used for the real geometry configuration.

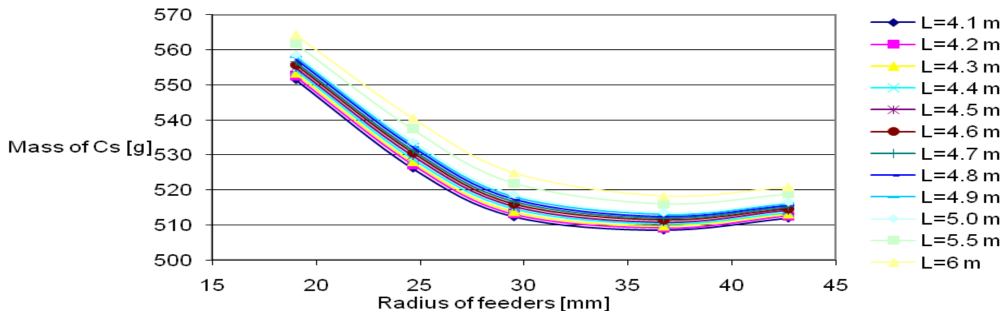

Fig. 3. The dependence of Cs mass on the radius of horizontal feeders for different lengths

In order to verify the validity and limitations of the approach, some cases have been analysed by comparison of the Cs, Sr and I deposited masses in ¼ CANDU PHT system using both Taylor approach (M1) and direct SOPHAEROS calculation (M2). Two ilustrative cases are presented in Table 3 where the first point has been chosen in the linear part of the curves and the second one in the non-linear part.

Table 3

The masses of Cs, Sr and I deposited in ¼ CANDU PHT, using M1 (Taylor approach) and M2 (direct SOPHAEROS calculation)

	Cs			**Sr**			**I**		
	M1 [g]	**M2 [g]**	**eps [%]**	**M1 [g]**	**M2 [g]**	**eps [%]**	**M1 [g]**	**M2 [g]**	**eps [%]**
x_1=23mm x_2=4.55m	536.20	536.52	-0.06	167.47	167.56	-0.06	166.01	166.09	-0.05
x_1=35mm x_2=4.95m	511.93	513.23	-0.25	163.19	163.36	-0.10	162.61	162.82	-0.13

The comparison shows an insignificant value of the relative error (eps) for the first case (x_1=23mm; x_2=4.55m) and very small differences for the second one. For this last case, the differences can be explained by an inappropriate polynomial fitting and the error may be reduced by the increase of the polynomial order degree.

From the point of view of source term evaluation the most interesting results consist of the FPs transferred masses to the containment. In Table 4 the transferred masses for Cs, Sr and I using both M1 and M2 methods, are presented.

Table 4

The masses of Cs, Sr and I transferred to the containment, calculated by M1 and M2 approaches

Calculation points		**Mass of FPs transferred to the containment [g]**	
		M1	**M2**
Cs	x_1=23mm, x_2=4.55m	2.1113E+03	2.1113E+03
	x_1=35mm, x_2=4.95m	2.1356E+03	2.1343E+03
Sr	x_1=23mm, x_2=4.55m	8.5653E+01	8.5557E+01
	x_1=35mm, x_2=4.95m	8.9929E+01	8.9766E+01
I	x_1=23mm, x_2=4.55m	8.2791E+01	8.2708E+01
	x_1=35mm, x_2=4.95m	8.6189E+01	8.5978E+01

The differences between M1 and M2 are very low. Thus, in the chosen limits of the dimensional classes for horizontal feeders, the M1 approach may be used in order to calculate the deposition and transport masses for a real structure of feeders by taking into account the number of feeders in each dimensional class. Therefore, a structure of M_d diameters classes and M_L length classes will have $\{D1, D2, ...D_{Md}\} \otimes \{L1, L2, ...L_{ML}\}$ real horizontal feeder classes. For each resulting class (*Di, Lj*) the M1 approach may be used to obtain the FPs deposition and transfer considering that all horizontal feeders have identical dimensions. Finally a weighted formula (3) may be used to evaluate the deposition for each isotope, *i*:

$$m_i^{dep} = \frac{1}{N} \sum_{j=1}^{Nclasses} N_j m_{i,j}^{dep} \tag{3}$$

where *Nj* is the number of feeders in each class (*Dj, Lj*) and *N* is the total number of feeders in the problem, $m_{i,j}^{dep}$ is the total deposition in the PHT for the isotope *i* and for dimensional class *j*. In this manner the uncertainties introduced by the representation of an averaged feeder in SOPHAEROS, may be reduced.

3. The user effect on using SOPHAEROS module

The user effect, which might introduce variability in the predicted results of code, represents an important uncertainty type, but it is not a common opinion in considering the user effect as an uncertainty source. Sometimes, it is embedded into three major sources of uncertainty that exist in accident analysis [2], sometimes is considered as a separate uncertainty source [9].

The user effect can be defined in the following modes:

- any difference in calculations that use the same code version and the same specifications (e.g. initial and boundary conditions) for a given plant or facility [10], [11];
- the influence of the code user on the predicted code results [12].

There are many important sources by which the users may influence the results. A brief description of some sources is presented in [13]: documentation of codes; nodalization; code options and physical model parameters; compiler and computer effects; specifications about initial and boundary conditions and time discretization.

To see the user effect in the final results (the FPs deposited masses and transferred into containment) obtained with SOPHAEROS V2.0 stand alone calculation, four models for ¼ CANDU PHT system are presented [13]:

- (M1): the model with 95 identical feeders (Fig. 1), having the average diameter as average mean of the feeders' diameters; it has been supposed that each class (D_1, D_2, D_3, D_4 and D_5) of feeders has 19 feeders; the mass flows are identical in each feeder;
- (M2): the model (Fig. 1.) with 95 identical feeders, having the average diameter obtained by conservation of transversal areas; the mass flows are identical;
- (M3): the model with 5 classes of feeders (Fig.4) (with 19 feeders in each class), having identical flows in each feeder;
- (M4): the model with 5 classes of feeders (Fig.4) but with different flows, which take into account the different transversal sections (table 5).

Table 5

Diameter of feeders for each class and mass flows

Class of diameters	Diameter of feeders [mm]	Surface [mm2]	Mass flow [Kg/s]	
			at t=T1=0	at t=T2 (>50 sec)
D1	38	1134.115	128.3	5.4
D2	49.3	1908.902	215.9	9.1
D3	59	2733.971	309.2	13.0
D4	73.4	4231.38	478.6	20.2
D5	85.4	5728.034	647.9	27.3
		Total	1780	75

In CANDU type reactors the horizontal feeders (also the horizontal fuel channels) act as a filter for the FPs [14]. In Table 6 the deposited masses of I, Cs and Sr, in horizontal feeders, can be seen. The masses were obtained with M1 and M3 models. An important and systematic difference can be observed in values offered by M1 and M3 models.

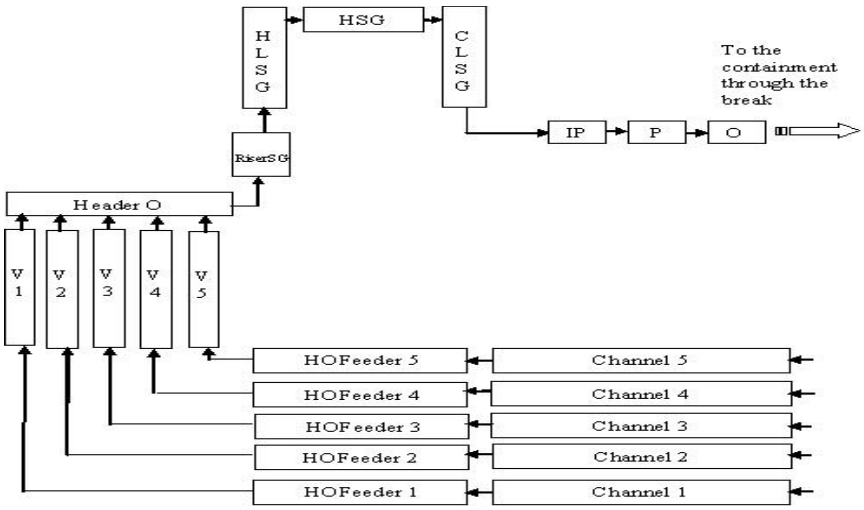

Fig. 4. ¼ CANDU primary circuit for M3 and M4

Table 6

Masses of FPs deposited in horizontal feeders, using M1 and M3

Model			
	I	Cs	Sr
M1	4.7297E-02	5.4469E-02	3.8726E-02
M3	6.4842E-02	7.2391E-02	5.1844E-02
(M1-M3)/M3 [%]	-27.1	-24.8	-25.3

Table 7 shows us that M3 model overestimates the values in comparison with M4, model in which a correction on flows has been made.

Table 7

Masses of FPs deposited in horizontal feeders, using M3 and M4

Model	FP	Deposited mass for each class of feeders [kg]					Total mass in horizontal feeders [kg]
		D1	D2	D3	D4	D5	
M3	Cs	3.1512E-02	2.1959E-02	1.2649E-02	4.3667E-03	1.9051E-03	7.2391E-02
	Sr	2.2541E-02	1.5400E-02	8.9343E-03	3.3531E-03	1.6157E-03	5.1844E-02
	I	2.8961E-02	1.9562E-02	1.1028E-02	3.7009E-03	1.5900E-03	6.4842E-02
M4	Cs	2.0332E-02	1.3734E-02	1.0268E-02	7.1712E-03	5.5582E-03	5.7064E-02
	Sr	1.2658E-02	9.3493E-03	7.2920E-03	5.1897E-03	3.9000E-03	3.8389E-02
	I	1.4814E-02	1.1038E-02	8.7119E-03	6.4025E-03	5.0892E-03	4.6055E-02

In Table 8 the comparison between M1, M2, M3 and M4 cases, regarding masses of Cs, Sr and I deposited in horizontal feeders is presented. Models M1 and M4 offer closed values and the differences may be explained based on the numerical approximation of transport, deposition and chemical species evolution models.
The closeness between M4 and M1 demonstrates that in these models we have equivalent deposition surfaces and equivalent flows.

Table 8

M1, M2, M3, M4 comparison for FPs deposition in horizontal feeders

FP	(M2-M1)/M1 [%]	(M3-M2)/M2 [%]	(M3-M1)/M1 [%]	(M4-M1)/M1 [%]	(M4-M2)/M2 [%]	(M4-M3)/M3 [%]
Cs	-15.8	24.4	32.9	4.8	24.4	26.9
Sr	-15.0	16.6	33.9	-0.9	16.6	35.0
I	-16.1	16.1	37.1	-2.6	16.1	40.8

The same closeness between M1 and M4 can be observed also in Table 9, when a comparison between the four models is made, regarding masses of Cs, Sr and I transferred into containment.

Table 9

M1, M2, M3, M4 comparison for FPs transfer to the containment

Model	**Mass of I [kg]**	**Mass of Cs [kg]**	**Mass of Sr [Kg]**
M1	**3.40E-02**	**9.00E-01**	**2.40E-02**
M2	3.60E-02	9.00E-01	2.60E-02
M3	2.50E-02	8.90E-01	1.80E-02
M4	**3.30E-02**	**8.90E-01**	**2.40E-02**

The results of the analyzed cases show that the influence of the user decision on the choice of data, might lead to relevant differences in the final results and consequently the user experience and the available data are important factors.
As have been mentioned above, an important user's, effect is the nodalization. The responsability of user to create a nodalization scheme is large and his/her effort to establish an adequate level of nodalization is important.

In reference [15] the influence of horizontal feeders' nodalization on FPs masses deposited in ¼ CANDU primary circuit (Fig. 1), during a postulated severe accident has been analyzed. The feeders' length has been divided in 5, 4, 3 and 2 nodes; for each situation (C5, C4, C3 and C2), the FPs deposited and transferred masses have been calculated by using SOPHAEROS V1.3.

In Table 10 and Table 11 only the masses of I and Cs are presented. These FPs have been chosen because they are the most important from the source term calculation point of view.

Table 10

The masses of I deposited in PHT for different nodalizations (C5, C4, C3 and C2)

Node	Volume	Iodine [kg] for different nodalisations			
		C5	C4	C3	C2
1	Fuel channels	3.60E-01	3.60E-01	3.60E-01	3.60E-01
2	Horizontal feeders	**7.50E-04**	**9.80E-04**	**1.40E-03**	**2.30E-03**
3	Horizontal feeders	**6.60E-04**	**8.90E-04**	**1.30E-03**	**2.20E-03**
4	Horizontal feeders	**6.60E-04**	**8.80E-04**	**1.30E-03**	
5	Horizontal feeders	**6.60E-04**	**8.80E-04**		
6	Horizontal feeders	**6.60E-04**			
7	Vertical feeders	2.10E-02	2.10E-02	2.20E-02	2.20E-02
8	Horizontal outlet header	2.10E-02	2.10E-02	2.10E-02	2.10E-02
9	Riser	2.60E-02	2.60E-02	2.60E-02	2.60E-02
10	Steam generator hot leg	5.20E-02	5.20E-02	5.30E-02	5.40E-02
11	Steam generator horizontal part	7.00E-03	7.00E-03	7.10E-03	7.10E-03
12	Steam generator coldleg	2.80E-02	2.80E-02	2.80E-02	2.80E-02
13	Pump – InPump element	8.50E-03	8.40E-03	8.30E-03	8.00E-03
14	Pump – Pump element	1.60E-02	1.60E-02	1.60E-02	1.50E-02
15	Pump – OutPump element	3.50E-03	3.50E-03	3.40E-03	3.30E-03
	Total deposition in horizontal feeders	**3.39E-03**	**3.63E-03**	**4.00E-03**	**4.50E-03**
	Total deposition in PHT	**5.46E-01**	**5.47E-01**	**5.49E-01**	**5.49E-01**
	Transfer to containment	5.20E-02	5.10E-02	5.00E-02	4.90E-02

Table 11

The masses of Cs deposited in PHT for different nodalizations (C5, C4, C3 and C2)

Node	Volume	Caesium [kg] for different nodalisations			
		C5	C4	C3	C2
1	Fuel channels	3.30E-01	3.30E-01	3.30E-01	3.30E-01
2	Horizontal feeders	**8.00E-04**	**1.10E-03**	**1.50E-03**	**2.60E-03**
3	Horizontal feeders	**7.10E-04**	**9.70E-04**	**1.40E-03**	**2.50E-03**
4	Horizontal feeders	**7.10E-04**	**9.70E-04**	**1.50E-03**	
5	Horizontal feeders	**7.10E-04**	**9.70E-04**		
6	Horizontal feeders	**7.10E-04**			
7	Vertical feeders	1.90E-02	1.90E-02	2.00E-02	2.10E-02
8	Horizontal outlet header	2.30E-02	2.30E-02	2.40E-02	2.40E-02
9	Riser	2.80E-02	2.80E-02	2.90E-02	2.90E-02
10	Steam generator hot leg	5.00E-02	5.10E-02	5.20E-02	5.40E-02
11	Steam generator horizontal part	7.20E-03	7.20E-03	7.30E-03	7.50E-03
12	Steam generator coldleg	2.90E-02	2.90E-02	3.00E-02	3.00E-02
13	Pump – InPump element	9.50E-03	9.50E-03	9.40E-03	9.30E-03
14	Pump – Pump element	1.80E-02	1.80E-02	1.80E-02	1.80E-02
15	Pump – OutPump element	3.90E-03	3.90E-03	3.80E-03	3.80E-03
	Total deposition in horizontal feeders	**3.64E-03**	**4.01E-03**	**4.40E-03**	**5.10E-03**
	Total deposition in PHT	**5.21E-01**	**5.23E-01**	**5.28E-01**	**5.32E-01**
	Transfer to containment	8.90E-01	8.90E-01	8.80E-01	8.80E-01

The results show that the influence of the nodalization is important at the level of local distributions (more exactly the position of the deposition), but is less sensitive at the level of transferred masses and total deposited masses. For example in case of I the maximum difference (between C2 and C5 situations) for total deposited mass is around 0.5%, whereas for Cs is 2 %. For mathematical and physical reasons the nodes should be as small as possible in order to reduce the averaging effect of the functions. From the numerical point of view, a great number of nodes lead to important computing requirements (both memory and executing time). At the same time the choice of very small nodes may introduces slow convergence and even numerical instabilities. The using of too large nodes implies systematically deviations from the expected results (experimental results or the predicted results based on the numerical behavior extrapolation/other codes' results).

4. Uncertainty Analysis for FPs Transport in CANDU PHT

Generally speaking, the objective of an uncertainty analysis (UA) for SAs is to facilitate accident management strategies [1]. There are many methods to assess uncertainties, most of them being developed and used for DBA analysis with best estimate analysis codes [3, 4] and [16-18]:

- the uncertainty method based on accuracy extrapolation (UMAE), developed by the University of Pisa, Italy;
- the AEA-T method, developed by AEA Technology, UK;
- the IRSN method using SUNSET (a Statistical UNcertainty and Sensitivity Evaluation Tool) developed by Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France;
- the GRS method, developed by Gesellschaft für Anlagenund Reaktorsicherheit (GRS), Germany;
- the ENUSA method, developed by Empresa Nacional del UIranio, SA (ENUSA), Spain;
- the code scaling, applicability and uncertainty methodology, developed by the United States Nuclear Regulatory Commission.

These methods have not yet been applied extensively to real plant severe accident analysis. Uncertainty analyses with SUNSET and ASTEC have demonstrated that this method is suitable for severe accident analysis [18, 19].

The aim of the UA presented in this paper is to obtain the domains of the output variables (for this study masses of Cs, Sr and I deposited in CANDU PHT system and its nodes – Fig. 1), taking into account the associated input parameters uncertainties. To do this, the following steps have been done:

- the identification of key parameters and uncertainty quantification;
- the uncertainty propagation through SOPHAEROS module;
- the uncertainty characterization in the final results.

4.1. The key parameters used for UA and uncertainty quantification

To identify the parameters for which an UA has to be carried out, firstly, a sensitivity analysis has to be performed.

Taking into account the results of the sensitivity study achieved in [20], five uncertain parameters have been chosen as having an important impact on the final results of the SOPHAEROS module:

- the starting time for the releasing process (t_em_1);
- the duration of the releasing process (*dt*);
- the releasing fraction for Cs (*f_Cs*);
- the releasing fraction for Sr (*f_Sr*);
- the releasing fraction for I (*f_I*).

These parameters are treated as random variables and the probabilistic modelling of uncertainty has been adopted. The normal probability density function – *pdf* (4) has been chosen to quantify the uncertainties of the five key parameters:

$$f\left(x, m, \sigma^2\right) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-m)^2}{2\sigma^2}} \tag{4}$$

where m and σ^2 represents the mean respectively the variance of the distribution.

To obtain an appropriate cover of the range of all parameters, a Monte Carlo simulation solution was adopted. A dedicated software application has been written in order to generate aleatory values for each of the five uncertain parameters. The main features are [21]:

- for each parameter, a_i, based on own experience or expert judgment, the interval of definition $[a_{i,min}, a_{i,max}]$ and the parameters of the distribution (*m* and σ^2) are defined by the user;
- the number of subintervals, N_i, of each interval of definition $[a_{i,min}, a_{i,max}]$ is also defined by the user; in each subinterval an uniform generating of the parameters' values is adopted;
- a total number M of generating values for each parameter is chosen by the user, taking into account the number of Monte Carlo simulations.

The generating method adopted consists of [21]:

- the area of normal *pdf* corresponding to the definition interval $[a_{min}, a_{max}]$ of parameter *a* is divided in *N* intervals $\left[a_{\min}, a_{\max}\right] = \bigcup_{i=1}^{N}\left[a_i, a_{i+1}\right]$;
- for each subinterval $\left[a_i, a_{i+1}\right]$ (Fig. 5.) a probability of occurrence of the value of the uncertain parameter in this interval is calculated as in (5):

$$p_i = \frac{\int_{a_i}^{a_{i+1}} f(x,m,\sigma^2)dx}{\int_{a_1}^{a_2} f(x,m,\sigma^2)dx} \qquad (5)$$

- corresponding to this probability and having in mind the total number of values we want to obtain (M), in each subinterval $[a_i, a_{i+1}]$, a number $K_i = p_i M$ of values are randomly generated for each parameter, as $\sum_{i=1}^{N} K_i = M$;
- a set of values $S_j = \{a_1^j, a_2^j, a_3^j, a_4^j, a_5^j\}$ is formed by randomly extracting values for each five key parameter ($a_i, i = 1,...5$) described above from the M randomly generated before values;
- each set of values is automatically written in the input file of the SOPHAEROS module.

For the uncertain parameters used in analysis, the input data defined by user are presented in Table 12.

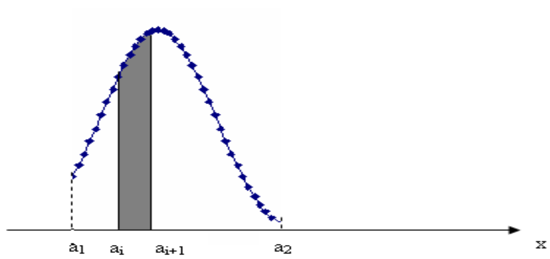

Fig. 5. The discretization of the normal distribution

Table 12

The input data defined by user, to generate aleatory values for key parameters

Uncertain parameter	a_1	a_2	m	σ	N_i
t_em_1 [s]	100	200	150	20	30
dt [s]	5	35	15	10	30
f_Cs	0.05	0.25	0.10	0.05	30
f_Sr	0.01	0.10	0.05	0.05	30
f_I	0.05	0.25	0.10	0.05	30

4.2. Uncertainty propagation through SOPHAEROS module

The propagation of the uncertainties from the uncertain parameters to the results through the computer code, requests a numerical estimation and this is obtained thanks to a

Monte Carlo simulation. In Monte Carlo simulation, the model is run many times (100, 500, 1000 or more), each time, for each uncertain parameters using different values. The values of each uncertain parameter respect its probability density function. The results of the Monte Carlo simulation lead to a sample of the same size for each code response. This sample is used then to calculate the typical statistics (the mean, median, mode, variance, standard deviation, etc) and to determine the cumulative distribution function (*cdf*). From *cdf* can be obtained cumulative percentiles (values bellow which specified percentage of the generated data for output fall) [22, 23].

In order to perform the UA for our case, a number of sets of values for the parameters involved is necessary. Each set will contain a different value for each uncertain parameter. The structure is:

```
Set1: val1_par_1
      val1_par_2
      -------------
Set2: val2_par_1
      val2_par_2
      -------------
………………………….
```

where:

val1_par_1 represents the first value of the first uncertain parameter;
val1_par_2 represents the first value of the second parameter;
val2_par_1 represents the second value of the first parameter;
val2_par_2 represents the second value of the second parameter, etc.

For this study, 500 sets of aleatory values obtained inside the intervals presented in table 12, have been created. The structure of some sets is presented in Fig. 6.

An input file is automatically created for each set of values by incorporating the set into a template input file. Therefore the automatic procedure avoids the common errors introduced by the construction of a large number of similar input files. Finally *M* input files prepared for a repeated run of SOPHAEROS module are available [21].

```
*** Final sets of values ***
 Set          1
(t_em1= 111.2    )
(dt   = 6.517    )
(f_Sr =0.8666E-01)
(f_Cs =0.1224    )
(f_I  =0.9892E-01)
 Set          2
(t_em1= 172.8    )
(dt   = 14.07    )
(f_Sr =0.1910E-01)
(f_Cs =0.1237    )
(f_I  =0.8740E-01)
 Set          3
(t_em1= 171.2    )
(dt   = 7.735    )
(f_Sr =0.3937E-01)
(f_Cs =0.1038    )
(f_I  =0.1162    )
.
...................
...................
 Set        497
(t_em1= 160.9    )
(dt   = 27.41    )
(f_Sr =0.7143E-01)
(f_Cs =0.1652    )
(f_I  =0.1664    )
 Set        498
(t_em1= 170.2    )
(dt   = 17.43    )
(f_Sr =0.9706E-01)
(f_Cs =0.8685E-01)
(f_I  =0.1054    )
 Set        499
(t_em1= 168.5    )
(dt   = 27.73    )
(f_Sr =0.4569E-01)
(f_Cs =0.6773E-01)
(f_I  =0.6312E-01)
 Set        500
(t_em1= 161.9    )
(dt   = 14.21    )
(f_Sr =0.7692E-01)
(f_Cs =0.2111    )
(f_I  =0.1360    )
```

Fig. 6. The structure of some sets of values for the uncertain parameters

4.3. The uncertainty characterization in the final results

A repeated run of the SOPHAEROS module, has been performed for M = 500. Finaly, the following responses of the computer code have been obtained [21]:

- 500 values of Cs mass deposited in ¼CANDU PHT and in its 11 nodes;
- 500 values of Sr mass deposited in ¼CANDU PHT and in its 11 nodes;
- 500 values of I mass deposited in ¼ CANDU PHT and its 11 nodes.

The masses of Cs, Sr and I deposited in ¼ CANDU PHT system (Fig. 1.) have been obtained, but for illustration, only graphical presentation for mass of Cs is shown in Fig. 7.

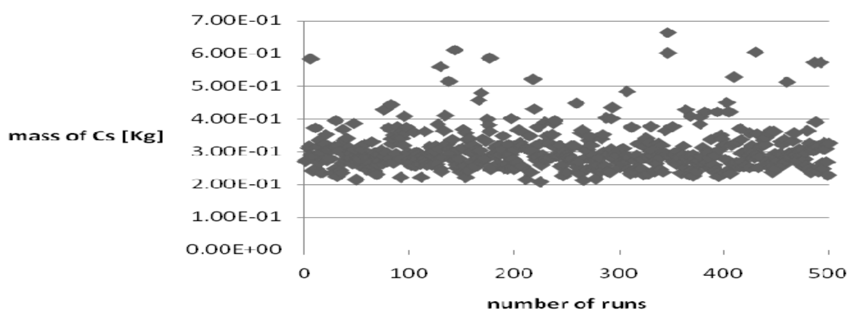

Fig. 7. The mass of Cs [Kg] deposited in ¼ CANDU PHT system

The results of this Monte Carlo simulation have led to 36 samples, such as [21]:

- 3 samples representing the mass of Cs, Sr and I deposited in ¼ CANDU PHT system;
- 33 samples representing the mass of Cs, Sr and I deposited in each of the 11 nodes of modelled CANDU PHT.

From each of the 36 samples, typical statistics such as mean, median or standard deviation (*stddev*) have been calculated and in order to obtain the range of the output values for the results of interest, containing the influence of uncertain parameters, the maximum (*max*) and minimum (*min*) value have been obtained. For illustration, only those values for mass of Cs are presented in table 13.

Table 13

The typical statistics for Cs deposited in ¼ CANDU PHT

	min	**max**	**median**	**mean**	**stdev**
PHT	0.2070	0.6650	0.2900	0.3040	0.0648
Node1	0.0153	0.4220	0.0587	0.0740	0.0580
Node2	0.0071	0.0489	0.0154	0.0182	0.0081
Node3	0.0083	0.0470	0.0217	0.0232	0.0082
Node4	0.0150	0.0381	0.0242	0.0250	0.0050
Node5	0.0183	0.0466	0.0300	0.0309	0.0062

Node6	0.0225	0.1030	0.0559	0.0572	0.0161
Node7	0.0048	0.0109	0.0075	0.0076	0.0009
Node8	0.0185	0.0484	0.0306	0.0310	0.0042
Node9	0.0016	0.0172	0.0114	0.0106	0.0036
Node10	0.0026	0.0430	0.0213	0.0216	0.0095
Node11	0.0005	0.0085	0.0046	0.0046	0.0020

To define the probability distribution of the variables given by SOPHAEROS module, containing the influence of the 5 uncertain parameters, we used cumulative distribution function. The *cdf* allows to get quantitative insights regarding the percentiles of the distribution. Only consideration about 3 variables, each of them containing 500 values, have been obtained: mass of Cs, Sr, respectively I deposited in ¼ CANDU PHT system.

For fitting empirical distributions to each of 500 values given by SOPHAEROS code response, the frequency histogram for Cs, Sr and I masses deposited in modelled CANDU PTH system have been obtained firstly and then, the *cdf*s. Finaly, as a statistical method of analysing results, cumulative percentiles are calculated, as can be seen in Table 14 [21].

The cumulative percentiles are values which the specified percentage of the generated data for an output fall (e.g. $x_{0.95}$ is the value that 95% of the generated data were less than or equal to). Differences between cumulative percentiles are used as a measure of the variable's range (e.g. $x_{0.95} - x_{0.05}$ would include the middle 90% of the possible output values). Table 14 presents the cumulative percentiles, calculated using PERCENTILE Excel function, for 3 variables (masses of Cs, Sr and I deposited in ¼ CANDU PHT system).

Table 14

The cumulative percentiles for variables of interest

	5% percentile	95% percentile
Mass of Cs [Kg]	0.2235	0.6465
Mass of Sr [Kg]	0.0355	0.2875
Mass of I [Kg]	0.0339	0.1581

The propagation of the uncertainties from the 5 uncertain parameters to the masses of Cs, Sr and I, deposited in ¼ CANDU PHT system using Monte Carlo simulation, offers by means of *cdf*s, quantitative insights regarding the percentiles of the distributions. In our cases, the intervals (0.2235, 0.6465), (0.0355, 0.2875) and (0.0339, 0.1581) would include the middle 90% of the possible masses [Kg] of Cs, Sr and I deposited in ¼ CANDU PHT system.

5. Conclusions

(1) The influence of model uncertainty is very important in the transport of fission products in CANDU type reactor, having relevant influences in the final results of the analysis. By means of the proposed methods: weighed mean and the interpolation approach based on Taylor expansion, the model uncertainty derived from the inadequacy between the complex geometry of CANDU PHT and the geometry modeled with SOPHAEROS, can be solved.

(2) The results of the analyzed cases show that the user effect can not be avoided, this having an important effect in the final results. The choosing of user decision on data used depends on the user experience and available data. The level of nodalization is dependent on the purpose of calculation taking into account the accuracy of the final results, the scope of calculation and the computing requirements.

(3) To obtain the influence of the five uncertain parameters on the final result (masses of Cs, Sr and I deposited in CANDU PHT system and its nodes), an uncertainty analysis has been performed. A method and flexible software have been developed in order to generate aleatory values for each of the five uncertain parameters. Inside an interval specified by the user, a specified number of aleatory values which respect the normal *pdf*, is generated.

(4) 36 samples have been obtained, using 500 sets formed by randomly extracting values for each of the five key parameters. For every sample, typical statistics as mean, median or standard deviation, have been calculated. As a statistical method of analyzing results, the cumulative percentiles for variables of interest have been obtained.

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