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Application of the ASTECv2.1.1.6 Severe Accident Computer Code and SUNSET Tool for Uncertainty and Sensitivity Analyses on MCCI VVER1000 Test Case

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Abstract. This article concerns an uncertainty and sensitivity investigation of certain parameters in the molten corium concrete interaction (MCCI) test case for VVER1000. It has been used the MEDICIS/ASTECv2.1.1.6 severe accident computer code to describe the basic parameters behaviour and the main phenomena arising during the MCCI in VVER1000 reactor design. The uncertainties in some parameters in the deterministic calculations requires additional investigations. An opportunity for an uncertainty and sensitivity analyses gives SUNSET computational tool which is a part of ASTEC computer code. In this article it have been investigated an influence of eight input parameters on two basic output parameters. It was found out to what extent each one of the eight input parameters affect on the studied output parameters. There also have been collected two groups of input parameters determining the maximal and minimal ranges of the output parameters uncertainties.

Keywords: Molten Corium Concrete Interaction, Severe accident, VVER-1000, ASTEC v2.1.1.6 computer code, SUNSET tool

1 Introduction

In case of a severe accident in the NPP reactor core could be overheated and a molten pool called corium could be generated at the bottom of the reactor vessel. This molten pool will consist mainly of uranium oxides, zirconium oxides, steel oxides and fission products. If the reactor vessel failure occurs this corium will enter in the containment basemat and will start to interact with reactor pit concrete called cavity. That's why it is very important to study the process of molten corium concrete interaction (MCCI) and the concrete ablation because the concrete appears the last barrier, which preserves fission products (FP) release to the environment.

ASTEC (Accident Source Term Evaluation Code) code was developed by the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) and the German Gesellschaft für Anlagen und Reaktorsicherheit (GRS) gGmbH from the late 1990s. Now the code is developed and maintained by IRSN [1–3].

The analyses on MCCI mainly concern improving the broad matrix of ASTEC\MEDICIS [4, 5] for better simulation of ex-vessel physicochemical processes during MCCI at real NPPs, such as PWR, VVER and etc. From one side the results obtained from the experiments like VULCANO (VB-U5, VB-U6 and VB-U7) [6], CLARA [7], COMETA, etc. are used for enriching the existing input models of the different reactor types. These experiments are jointly analyzed and the obtained solutions are used to improve the existing European codes. From the other side the real plant test case, where one particular scenario has been simulated and analyzed by MCCI codes like MEDICIS and others, helps also for better understanding of MCCI. The final goal of the investigations is to provide analytical tools for description of MCCI phenomena at real NPPs as VVERs, PWRs, etc. and to generate proposals for corium management strategies.

The reference nuclear power plant that was chosen for this MCCI test-case investigation is VVER-1000. The initial conditions for MCCI test are taken after SBO scenario calculated with ASTEC version 1.3R2 by INRNE.

In the frame of the European Severe Accident Research Network of Excellence (SARNET2) project a benchmark on the same VVER1000 MCCI test [8, 9] was organized. Based on the ASTECv1.3R2 calculation a "Benchmark Definition report of reactor test-case" [10] has been prepared to specify the obligatory parameters for benchmark comparison. The technical report summarizes VVER1000 geometry of reactor core, cavity, concrete basemat and initial conditions necessary for MCCI test-case after SBO scenario. The thermodynamic calculations in corium-concrete pseudo-binaries have been determined from GEMINI2 calculations using the NUCLEA 08 database by IRSN. Different codes like MEDICIS (ASTECv2) and WECHSL have been used to describe the main phenomena during the interaction between real concrete material from the reactor pit and the corium. Many scientific organizations as IRSN France, INRNE Bulgaria, EI Bulgaria, TU Bulgaria, GRS Germany, KIT Germany and NUBIKI Hungary have been involved to recalculate and explain pool/concrete interface behavior.

The calculation results of MCCI VVER1000 test showed that different researchers often use different values of the initial parameters to model one and the same test case with ASTEC code. This happens due to the ability some parameters and approaches to be chosen by the user. So, the main task of this study is to demonstrate how the different choice of the values of eight input parameters will influence on the two basic output parameters.

Parameters in the VVER1000 MCCI test case which are investigated:

- (e1) — TABLA – temperature of the concrete ablation;
- (e2) — GAS temperature – gas temperature in the bulk;
- (e3) — HSLAG (oxide layer) – Slag layer heat transfer coefficient between the oxide layer and basemat concrete;
- (e4) — LCRUST (oxide layer) – Conductivity coefficient of the crust between the oxide layer and basemat concrete;
- (e5) — HSLAG (metal layer) – Slag layer heat transfer coefficient between the metal layer and basemat concrete;
- (e6) — LCRUST (metal layer) – Conductivity coefficient of the crust between the metal layer and basemat concrete;
- (e7) — HSLAG (crust layer) – Slag layer heat transfer coefficient between the upper crust layer and basemat concrete;
- (e8) — PERMEABILITY (upper crust layer) – permeability of the upper crust layer.

The main result parameters that are analysed in this VVER1000 MCCI test case are:

- MERO – the mass of eroded concrete in the cavity;
- Mh2 – mass of the generated hydrogen.

In the nuclear power plants (NPP) severe accident analyses it has been used the best estimate approach which requires uncertainty analyses. The SUNSET computer tool [11–13] that works with ASTEC is a statistical tool and using a statistical methods for risk analysis studies. This tool helps to do both uncertainty statistical analyses as well as sensitivity analyses [14]. The estimation code SUNSET was used for the uncertainty and sensitivity analysis of the calculation results of the MCCI VVER1000 test case.

The uncertain input parameters and their possible range are specified in the SUNSET input at the beginning. Further, 100 calculation runs have been performed. The collections of input parameters in these 100 calculations are generated by the SUNSET at random using the Sample Random Sampling (SRS) method. It was done calculation for each group of input parameters and uncertainty analysis was perform. This allow to account the influence of each one of the eight input parameters on the MCCI VVER1000 test case.

The regression model was used to obtain global sensitivity measures of the effect of the input variables Xs (TABLA, T_{gas}, $HSLAG_{oxide}$, $LCRUST_{oxide}$, $HSLAG_{metal}$, $LCRUST_{metal}$, $HSLAG_{crust}$, $PERMEABILITY_{upper\ crust}$) on the variation of the dependent output variables Ys (in our case: MERO and Mh2). These output variables (MERO and Mh2) are defined in the PLOT structure of the input deck. The described example is illustrated at Figure 1.

Based on these uncertainty and sensitivity analyses two sets of parameters have been determined which bounded the maximal (worst) and the minimal (best) results for the investigated output parameters.

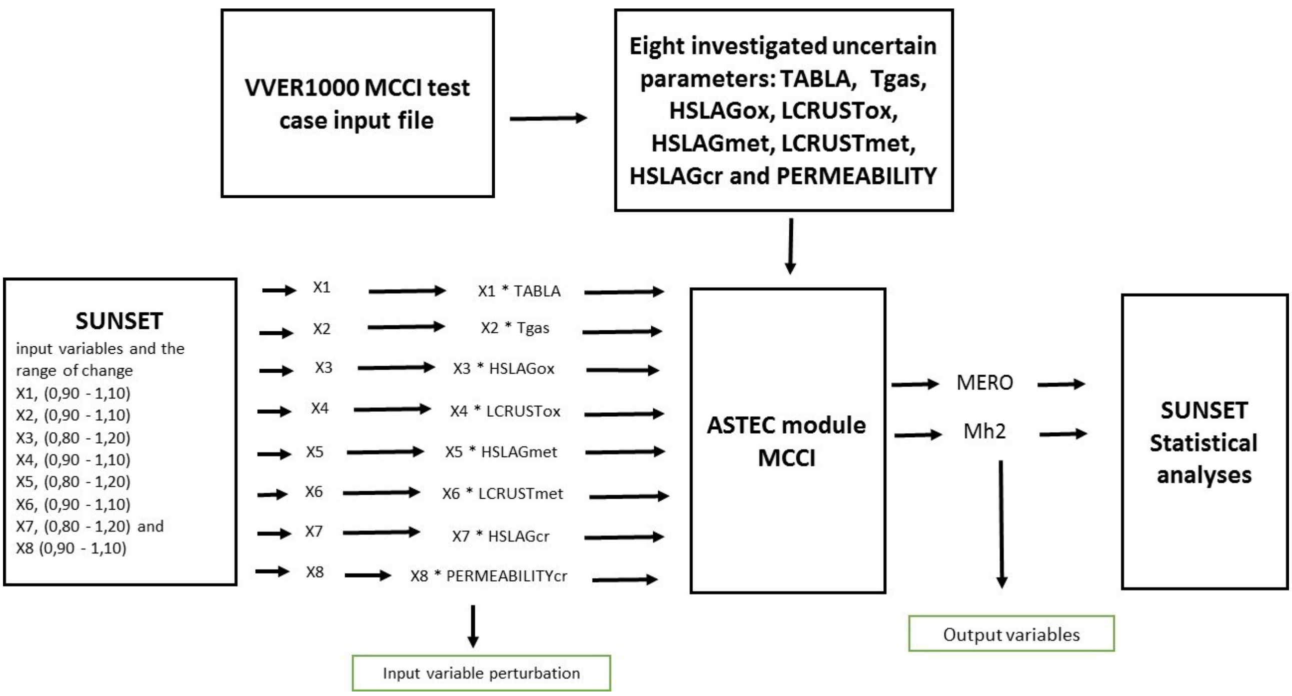

Figure 1. SUNSET/ASTEC VVER100 MCCI test case example.

2 The MEDICIS/ASTECv2.1.1.6 Input Model for the MCCI VVER1000 Test Case

The main assumptions in the basic ASTECv2/MEDICIS input model are presented in this section. The calculation starts when a corium slump from the vessel is transferred in the cavity. It is assess that the total corium slump (125277 kg) transferred to the cavity could be considered as two phase mixture, which consists from the heavier refractory oxides (UO_2 and ZrO_2) and pure metals (Fe, Cr, Ni and Zr). They stratified initially in the cavity forming two layers: oxide layer and metal layer. As the oxide layer is heavier initially it is positioned under the metal layer. The masses of the components in these layers are presented in Table 1.

Table 1. Corium pool composition

Metal layer composition		Oxide layer composition	
Fe	30000 kg	O_2U	74294 kg
Cr	4520 kg	O_2Zr	1700 kg
Ni	2620 kg		
Zr	12143 kg		

The initial temperature of the ejected corium is as follows: oxide layer has temperature of 2879 K but the metal layer has temperature of 2673 K.

The convective heat transfer in the bulk pool is determined by Bali correlation. Heat transfer between the oxide and the metal layers is determined by Greene correlation. The local heat flux from the pool to the concrete is determined by heat transfer coefficient (HSLAG) of the interface structure between the corium and the concrete called "slag layer". The other important parameter impacting on the ablation kinetics is GAMMA parameter. GAMMA determines pool solidification temperature. The basic calculation assumptions are GAMMA $= 0.3$ and HSLAG $= 1000$ W/(m^2.K). Solidus and liquidus temperatures vs. composition of the melt pool were calculated by GEMINI02 computer code using the NUCLEA09 database.

During the MCCI a crust can appear at the pool/concrete interface. The values for crust conductivity accepted in the ASTECv2.1.1.6/MEDISIS input are: $\text{LCRUST}_{\text{metal/concrete}} = 5$ W(m.K) and $\text{LCRUST}_{\text{oxide/concrete}} = 0.3$ W/(m.K).

Reactor pit concrete could be classified as a siliceous type with high content of iron in it. Simplified cavity geometry is used with a cylindrical reactor pit. The cavity is considered to be cylindrical with radius RCAV $= 3.0$ m. The height of the cavity is considered to be HCAV $= 6.3$ m. In radial direction the cavity concrete wall thickness EWALL $= 3.194$ m. The cavity basemat thickness in axial direction is HRAD $= 3.6$ m in accordance with the geometry of VVER1000 reactor. The calculations are pursued until axial basemat melt-through.

The mass fractions of the main concrete components are given in the Table 2.

Table 2. Reactor pit concrete composition

Concrete components	Mass fraction
CaO	0.2003
SiO_2	0.4736
Al_2O_3	0.01755
H_2O	0.04535
CO_2	0.067
Fe	0.1617
Fe_2O_3	0.021
MgO	0.0135

3 Uncertain Parameters and Their Range for MCCI VVER1000 Test Case

The reference value used in the basic MCCI VVER1000 test case calculation and their probable ranges are presented in Table 3. The uncertainty of the input parameters is determined from their ranges. It was assumed that the uncertain parameters presented in Table 3 could vary in the entire deviation range with the same probability. The uniform distribution was used for all 8 parameters.

4 Uncertainty Analyses

Using the SUNSET computer tool and ASTECv2.1.1.6 code, 100 different sets of uncertain input parameters were selected and after that 100 calculations were performed with MEDICIS.

The results from the MEDICIS/ASTECv2.1.1.6 calculations of the MCCI VVER1000 test case are presented in Figures 2 and 3. The the mass of eroded concrete in the cavity (MEROD) and the total mass of the generated hydrogen (Mh2) are presented.

The calculation results account two bounding cases: the bounding upper case and the bounding lower case. The average value also has been presented.

Table 3. Uncertain parameters

No	Parameter	Reference value	Deviation range (%)
e1	Temperature of the concrete ablation	1570 K	$\pm 10\%$
e2	Gas temperature in the bulk	1500 K	$\pm 10\%$
e3	Slag layer heat transfer coefficient between the oxide layer and basemat concrete	1000 W/(m^2.K)	$\pm 20\%$
e4	Conductivity coefficient of the crust between the oxide layer and basemat concrete	0.3 W/(m.K)	$\pm 10\%$
e5	Slag layer heat transfer coefficient between the metal layer and basemat concrete	1000 W/(m^2.K)	$\pm 20\%$
e6	Conductivity coefficient of the crust between the metal layer and basemat concrete	5.0 W/(m.K)	$\pm 10\%$
e7	Slag layer heat transfer coefficient between the upper crust layer and basemat concrete	1000 W/(m^2.K)	$\pm 20\%$
e8	Permeability of the upper crust layer	3.D-11 m^2	$\pm 10\%$

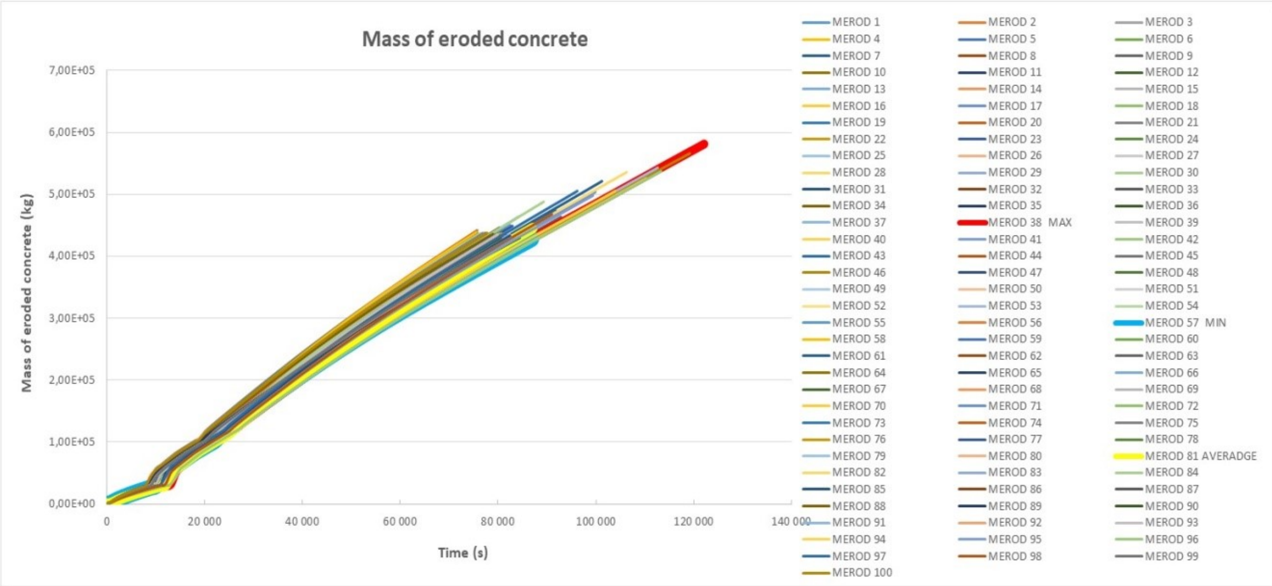

Figure 2. Mass of eroded concrete in the cavity (MEROD).

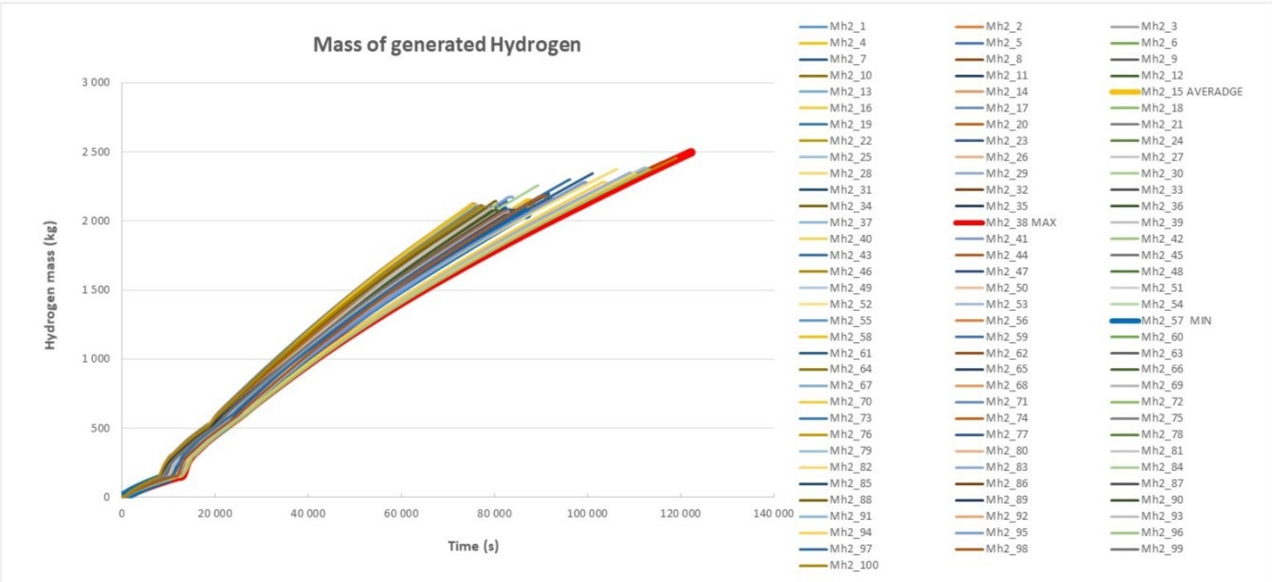

Figure 3. Mass of the generated Hydrogen (Mh2).

Table 4. Results from the classic statistical analysis for MEROD and Mh2

Output variable	Average	Standard deviation	min	max
'Outputs_variable#1' MEROD	451859.8	37417.2	428117.0	584292.0
'Outputs_variable#2' Mh2	2139.9	103.3	2055.6	2498.1

The presented results in Table 4 for the output variables MEROD and Mh2 give information about the average values, the standard deviation used to estimate the error due to the uncertainty and the minimal and maximal values summarized from the statistical analysis. The results correspond to these presented in Figures 2 and 3.

5 Sensitivity Analyses

For the investigated MCCI VVER1000 test case sensitivity analysis of the uncertain parameters on the calculation results was performed using the SUNSET computer tool.

The influence of the eight uncertain parameters pointed in Table 3 on the mass of eroded concrete in the cavity (MEROD) for MCCI VVER1000 test case is presented in Figure 4.

As seen from Figure 4 the biggest influence on the MEROD and Mh2 have: temperature of the concrete ablation – TABLA (parameter number 1), Conductivity coefficient of the crust between the oxide layer and basemat concrete – $LCRUST_{oxid\_layer}$ (parameter number 4), and Slag layer heat transfer coefficient between the metal layer and

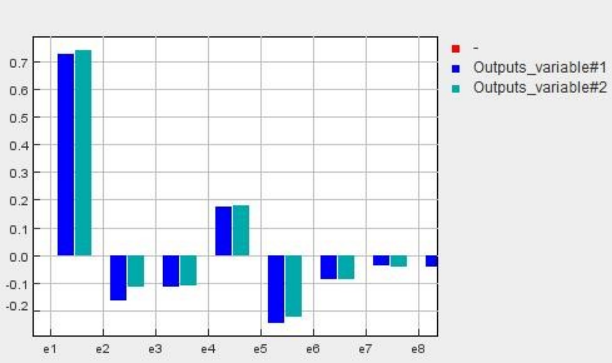

Figure 4. Influence of uncertain parameters to the mass of eroded concrete (Outputs_variable#1: MEROD) and to the mass of generated hydrogen (Outputs_variable#2: Mh2) compute by SUNSET.

basemat concrete – $HSLAG_{metal\_layer}$ (parameter numbers 5). Parameter number 5 have negative influence to the calculation results; this means that the increase of this parameter leads to a decrease of MEROD and Mh2. From the other side, parameters numbers 1 and 4 has a positive influence. Increase of these parameters leads to increase of MEROD and Mh2.

The sensitivity evaluation by the SUNSET computer tool for the MCCI VVER1000 test case calculations showed that parameters number 2 and 3 (GAS temperature and $HSLAG_{oxid\ layer}$) are also important for the calculation results, and these parameters have a smaller negative influence.

The total amount of generated hydrogen is one of the most important parameters in the MCCI VVER1000 test case. The input parameters, affecting the calculated amount of generated hydrogen are the same as these affecting the calculated amount of the mass of eroded concrete.

6 Development of a Set of Parameters for Maximal (Worst) and Minimal (Best) Calculations

Based on the uncertainty and sensitivity analysis, performed with the SUNSET computer tool (evaluating the influence of input parameters to the calculation results), two sets of parameters (parameters that give the highest and lowest value of the mass of eroded concrete – MEROD and hydrogen generation – Mh2) were developed. In the set, where the goal was to obtain a larger amounts of MEROD and Mh2, all parameters which have a positive influence on concrete erosion and hydrogen generation were maximized within their variation range. Conversely, the parameters which have a negative influence to calculation results were minimized within their variation range. The set of parameters for the minimal amount of hydrogen was created in the opposite manner (Table 5). Maximal and minimal values of parameters were determined according to the reference values presented in Table 3.

The developed sets of input parameters were used for the calculation of the MCCI VVER1000 test case by employing the MEDICIS/ASTECv2.1.1.6 computer code using the same input model. The maximal and minimal values of parameters (Table 5) where entered in the same input file for the MCCI VVER1000 test case calculation.

7 Results from the Bounding Calculations

The results from the both bounding calculations with the maximal and minimal values of the eight input parameters are presented hereafter. Two MEDICIS/ASTECv2.1.1.6 code calculations were performed.

The MEDICIS/ASTECv2.1.1.6 computer code calculation results are presented in Figures 5 and 6.

The maximal value of the MEROD that has been reached is 884234 kg but the minimal value of MEROD is 438059 (Figure 5). As it seen from Figure 6 the maximal amount of Mh2 is 3308 kg. Conversely, the minimal value of generated Hydrogen is 2109 kg.

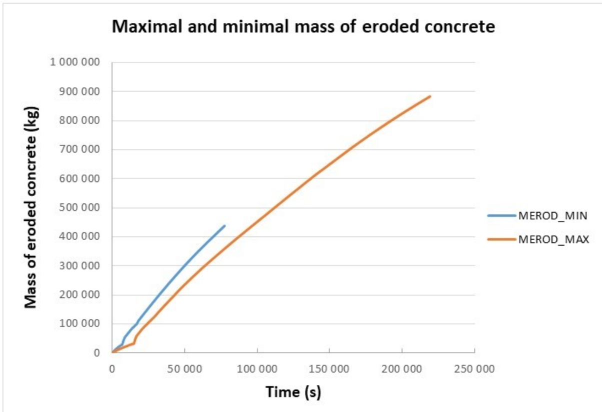

Figure 5. Maximal and minimal values of the mass of eroded concrete (MEROD).

Table 5. Input parameters for the calculation of maximal and minimal values

No	Parameter	Maximal calculation (%)	Minimal calculation (%)
e1	Temperature of the concrete ablation (K)	+10% Ref.	-10% Ref.
e2	Gas temperature in the bulk (K)	-10% Ref.	+10% Ref.
e3	Slag layer heat transfer coefficient between the oxide layer and basemat concrete [W/(m^2.K)]	-20% Ref.	+20% Ref.
e4	Conductivity coefficient of the crust between the oxide layer and basemat concrete [W/(m.K)]	+10% Ref.	-10% Ref.
e5	Slag layer heat transfer coefficient between the metal layer and basemat concrete [W/(m^2.K)]	-20% Ref.	+20% Ref.
e6	Conductivity coefficient of the crust between the metal layer and basemat concrete [W/(m.K)]	-10% Ref.	+10% Ref.
e7	Slag layer heat transfer coefficient between the upper crust layer and basemat concrete [W/(m^2.K)]	-20% Ref.	+20% Ref.
e8	Permeability of the upper crust layer (m^2)	-10% Ref.	+10% Ref.

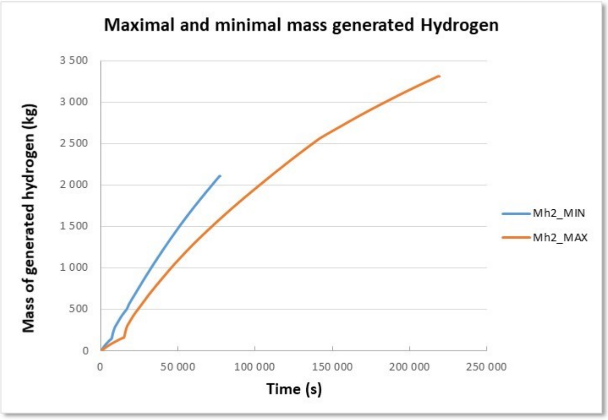

Figure 6. Maximal and minimal values of the mass of generated hydrogen (Mh2).

8 Conclusions

The MCCI VVER1000 test case was chosen as a reference case for investigation in this article. The main purpose is to evaluate the influence of eight input parameters (TABLA, T_{gas}, $HSLAG_{oxide}$, $LCRUST_{oxide}$, $HSLAG_{metal}$, $LCRUST_{metal}$, $HSLAG_{crust}$, $PERMEABILITY_{upper\ crust}$) on the two basic output parameters (MEROD and Mh2). In order to achieve this aim it was developed basic input deck for calculation with the MEDICIS module of ASTECv2.1.1.6 computer code for Kozloduy VVER1000 reactors. The possible uncertainties in the MEDICIS calculation were evaluated. Use of SUNSET computational tool together with MEDICIS/ASTECv2.1.1.6 allowed evaluating the influence of uncertain input parameters on the test results. 100 different sets of uncertain input parameters were selected on random and after that 100 calculations were performed with MEDICIS and analyzed by SUNSET.

The sensitivity analysis showed that initial input parameters, affecting the calculated amount of the mass of eroded concrete (MEROD) affect also the calculated amount of generated hydrogen (Mh2). The biggest positive influence on the MEROD and Mh2 have temperature of the concrete ablation (TABLA) and conductivity coefficient of the crust between the oxide layer and basemat concrete ($LCRUST_{oxid\_layer}$). The results were exhibited by the slag layer heat transfer coefficient between the metal layer and basemat concrete ($HSLAG_{metal\_layer}$). The influence of the other input parameters is negligible.

Taking into account the results of uncertainty and sensitivity analysis, two sets of parameters which give the highest (worst) and lowest (best) values of MEROD and Mh2 were developed. The results of the calculations, performed using the MEDICIS/ASTECv2.1.1.6 computer code with the both sets, showed the behavior of the maximal and minimal bounding values.

The results of analyses, performed in this article demonstrated that it is possible to use the SUNSET computational tool to evaluate only those parameters which have the biggest influence and to calculate the best and the worst bounding cases for the investigated output parameters. In this way the MCCI VVER1000 test case can be represented with the present range of uncertainties. It could help for adequate further modelling of the MCCI phenomena related VVER1000 design and better understanding of this kind of severe accidents

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