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ASTECV2.2b and SUNSET uncertainty and sensitivity analyses on IVMR WWER1000 Test Case

Rositsa Gencheva[a,*], Antoaneta Stefanova[a] and Pavlin Groudev[a]

[a]*Institute for Nuclear Research and Nuclear Energy – Bulgarian Academy of Sciences (INRNE-BAS), Tzarigradsko shaussee 72, 1784 Sofia, Bulgaria*

E-mail: r.gencheva@inrne.bas.bg, antoanet@inrne.bas.bg, pavlinpg@inrne.bas.bg

This article concerns an uncertainty and sensitivity investigation of certain parameters in the In-Vessel Melt Retention (IVMR) test case for Water-Water Energetic Reactor – 1000/v320 (WWER-1000/v320). It has been used the ICARE and CESAR modules of ASTECv2.2b severe accident computer code to describe the basic parameters behaviour and the main phenomena arising during the IVMR in WWER1000 reactor design. The external vessel water cooling has been chosen for IVMR strategy. First, one stand-alone calculation have been done to account the most heat loaded segment from the vessel.

After, the uncertainties in two parameters in the deterministic calculation have been investigated additionally to account their influence on the heat flux on this segment. An opportunity for an uncertainty and sensitivity analyses gives SUNSET (**S**tatistical **UN**certainty and **S**ensitivity **E**valuation **T**ool) software which is a part of ASTEC computer code. The SUNSET computational tool developed by IRSN, is a statistical tool designed for uncertainty and sensitivity analysis of mathematical or physical models like computer codes.

It have been investigated an influence of the different pressure values inside the vessel and influence of the different temperature values of outside cooling water on the two basic output parameters: heat flux on the most heat loaded segment of the vessel and the minimal vessel wall thickness of this segment. It was found out to what extent each one of the both input parameters effect on the studied output parameters.

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1. Introduction

The measures of Severe Accident Management (SAM) in the Nuclear Power Plants (NPP) are focused nowadays on the possibility to apply in-vessel melt retention (IVMR) strategy with external reactor vessel cooling (ERVC) in light water reactors (LWR). Water cooling of the outside surface of the reactor bottom vessel is one of the promising strategies for cooling the corium which is collected in the lower plenum of the reactor vessel after a severe accident in the Nuclear Power Plant (NPP). During a severe accident, the reactor core cooling could be disturbed or stopped, which will have caused the core melting and slump into the bottom of the reactor vessel. The purpose of this strategy is to retain the melted corium in the vessel and to prevent reactor vessel failure and fission product release in the containment. The implementation of this strategy requires ensuring the availability of a sufficient amount of water at the appropriate temperature on the outside of the reactor vessel in case of a reactor core melts and is poured into the reactor's lower plenum. For this purpose, the reactor cavity could be flooded with this water via passive safety systems, which do not require a pump or electrically forced water circulation. When the reactor cavity is filled with water this water can help to preserve the reactor lower plenum (LP) vessel integrity (in-vessel melt retention strategy).

T.G. Theofanous [1] mentioned the IVMR strategy for the first time in 1996. In his investigation, it has been investigated a Loviisa Water-Water Energetic Reactor (WWER) 440 lower plenum filled with corium that stratifies in oxide and metal layers. IVMR strategy has been approved as SAM strategy for the first time in Loviisa WWER440 NPP. It has been used an ice-condenser containment for supplying the cavity with water and ensuring the reactor vessel bottom head cooldown. To simulate the corium melting pool in the lower plenum for the Loviisa reactor design a benchmark was organized [2]. In the benchmark, there have been used different severe accidents computer codes to simulate the reactor lower plenum external water cooling. The approach for corium melting pool stabilization has been launched.

This work concerns IVMR strategy investigation with ERVC. The reference plant of this investigation is WWER1000/v320 NPP. To simulate the corium melting pool phenomena in the LP during the vessel external water cooling the ICARE and CESAR modules of ASTECv2.2b computer has been used. The developers of the ASTEC (Accident Source Term Evaluation Code) computer code [3, 4] for simulation of severe accidents at light water reactors are the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) and the German Gesellschaft für Anlagen und Reaktorsicherheit (GRS). The ASTEC code is currently under development by IRSN [5, 6, 7]. The ASTEC computer code is applicable and provides support for the safety assessment of Light Water Reactors (LWR), such as the WWER1000 type [8, 9, 10].

The investigated event in this work is a Large Break Loss of Coolant Accident - LB LOCA (guillotine break in the cold leg) and Station Blackout (SBO) at the same time in the WWER1000/v320 reactor design. The reference NPP is Kozloduy, Unit 6. The reactor SCRAM occurs 1 sec after the SBO due to a signal for stopping of three Main Coolant Pumps (MCP). The passive safety systems such as Hydro-accumulators are not available in this simulation. The accident was prolonged with faster coolant depletion and evaporation through the break, core overheating and degradation, melting pool formation, melting of internal core structures, barrel failure, and pouring of the corium melt in the LP of the WWER1000 reactor. In this scenario, the accident develops relatively quickly and quickly turns into a severe accident. Faster transient evolution leads to higher decay heat generated in the molten corium.

WWER1000 test case starts after the initiation of LB LOCA and SBO accident mentioned above, at the moment when a huge mass of molten corium that consists of melted core and supported internal core structures slumps into the LP of the reactor vessel. Our simulation of the WWER1000 test case is a simplified stand-alone calculation done with ASTECv2.2b where just the LP vessel and the corium in it were modelled in the input. We assumed that the coolant is evaporated at this moment so, the water in the LP wasn't modelled in the input. The initial and boundary conditions that concern the composition of the corium, the masses of the main components of the melted pool, initial temperature of the corium, initial pressure inside and outside the vessel LP, the temperature of the water in the cavity that is in contact with the outside surface of the vessel, the decay heat that is generated by the fission products in the melt pool and etc. have been taken from the specifications of previous investigations of this WWER1000 test case [11, 12, 13, 14].

The calculation continues with increasing the corium pool temperature (due to decay heat), melt pool stratification in oxide and metal layers, and lower plenum vessel ablation until reaching thermochemical equilibrium conditions.

The aim of this basic calculation is to compute a heat flux profile along the internal and external surfaces of the vessel's lower plenum. Looking at the profiles it could be determined the most heat-loaded area of the LP in height. As the LP vessel has been discretized in the input model radially in rings and axially in segments, we can determine from this first basic calculation the most heat-loaded segment, the elevations and the location of this segment, the maximal heat flux over this segment, and also the thickness of this segment at the end of calculation when the thermochemical equilibrium has been established in the melted corium. So, we can summarize that the main purpose of this basic calculation is to distinguish the most heat-loaded segment of the LP vessel.

In the second part of this work, uncertainty and sensitivity calculations have been done by coupling ASTECv2.2b computer code and SUNSET mathematical and statistical tool [15, 16]. The influence of the variations in values of two input parameters on the two output parameters has been investigated. The first input parameter of great interest is inside vessel pressure. The second input parameter is the temperature of the cooling water outside the LP. The output parameters are strongly connected with the result from the first basic calculation, which is the determination of the most heat-loaded segment of the LP vessel. Both output parameters, that have been analyzed are the heat flux over the most heat-loaded segment and the thickness of the vessel in the most heat-loaded segment at the end of the calculation.

Input parameters that vary at a certain range in the IVMR WWER1000 test case:

P_{inside_vess} – The pressure inside the vessel;

$T_{water\_outside}$ - Cooling water temperature outside the vessel.

Result parameters that are analyzed in the IVMR WWER1000 test case:

$THIC_{most\ heat\ loaded\ segment}$ – thickness of the vessel in the most heat loaded segment;

$HF_{most\ heat\ loaded\ segment}$ – heat flux in the most heat loaded segment

The SUNSET statistical tool could be used to perform uncertainty and sensitivity analyses. In the beginning, it has been created a basic input for SUNSET/ASTECv2.2b, where the uncertain parameters have been pointed as "val:1" and "val:2". The ranges of their variations in reasonable margins have been pointed out. In the basic input have also been pointed the result parameters against which we examine the uncertainty parameters. In the discussed WWER1000 test case 50 inputs have been prepared for calculations with ASTECv2.2b. The selection of uncertainty input parameters for each one of these 50 calculations is randomly selected by SUNSET. The Monte-Carlo method for Simple Random Sampling (SRS) is used by SUNSET to generate the different 50 sets of input variables. The ASTEC input sample files containing the different sets of uncertain

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input variables are named “doncal” files. The next STEP consists of performing 50 ASTEC runs of 50 IVMR WWER1000 test case calculations. They are executed in 50 different directories created by SUNSET and containing the “doncal” files. The results from these 50^{th} calculations are collected in so-called PLOT fails. The outputs of two chosen output variables ($THIC_{most\ heat\ loaded\ segment}$ and $HF_{most\ heat\ loaded\ segment}$) have been collected in the plot files for each one of the 50^{th} calculations.

The last step consists of post-processing actions and analyses by SUNSET. The simple regression method is used to obtain sensitivity measures of the effect of the input variable variations (Xs) on the variation of the dependent variables (Ys). We consider a couple of numerical variables (X, Y), where X is the input variable or regressor but Y is the response variable or the output value. We consider that X is a known variable, while we want to express Y as a transformation on the X independent variable. The function determining the transformation uses the least squares method. The least squares method allows to determining of regression coefficients, the correlation coefficients as well as the coefficients of determination. The linear sensitivity module is used in our investigation to determine the correlation and the determination coefficients.

The scheme of uncertainty analysis done by coupling of SUNSET/ASTECv2.2b, based on (SRS) Monte-Carlo simulations is presented in Figure 1.

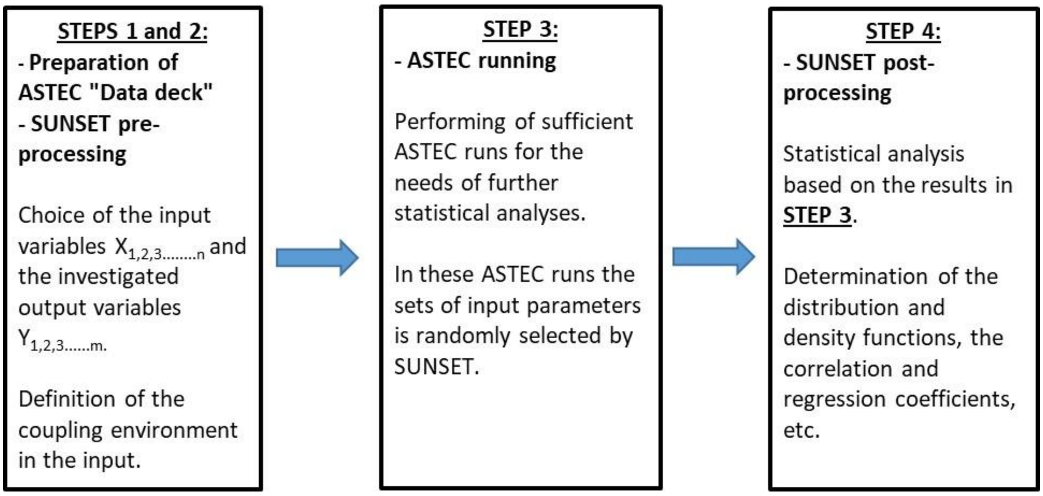

Figure 1.: Scheme of SUNSET/ASTEC coupling [16]

In our WWER1000 test case, there have been investigated the influence of the different pressure values inside the vessel (P_{inside_vess}) and the influence of the different temperature values of outside cooling water ($T_{water\_outside}$) on the two basic output parameters: minimal vessel wall thickness of the most heat-loaded segment of the vessel ($THIC_{most\ heat\ loaded\ segment}$) and the heat flux evolution on this segment ($HF_{most\ heat\ loaded\ segment}$).

The output result parameters correspond to Risk 2 (Risk of excessive heat flux on the vessel wall) and Risk 3 (Risk of excessive vessel ablation) from the PIRT developed during the H2020 IVMR project No 662157 [17].

The described example is illustrated in Figure 2.

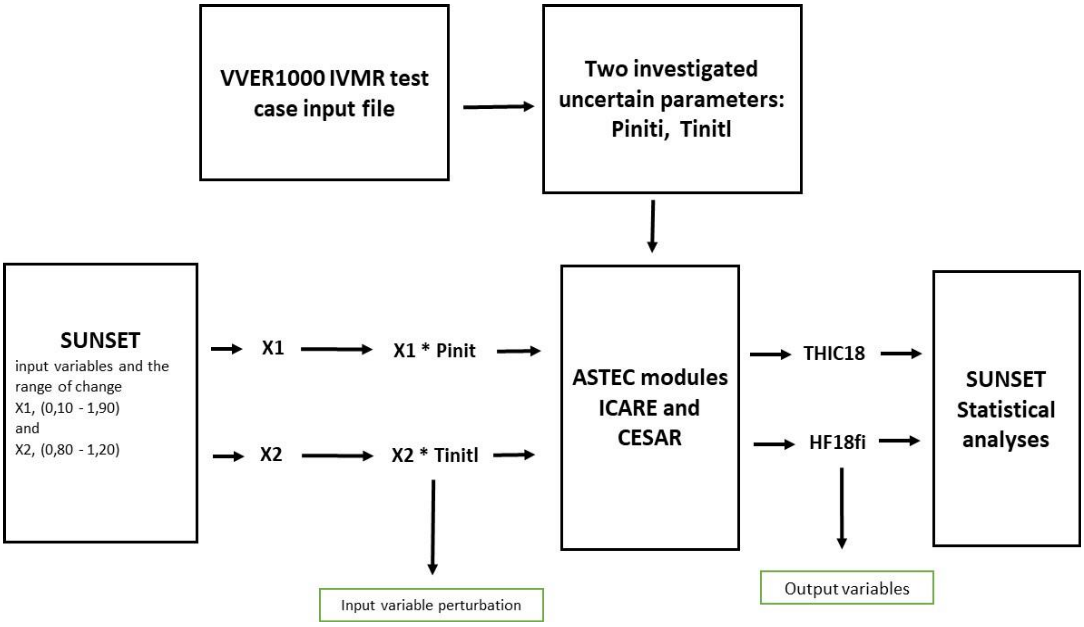

Figure 2: SUNSET/ASTECv2.2b IVMR WWER1000 test case example

2. Brief description of IVMR WWER1000 test case

As it was mentioned above a stand-alone calculation has been done with ICARE and CESAR modules of ASTECv2.2b computer code. For this basic calculation it was developed an ASTEC input model. The vessel lower plenum has been modeled without internals and without coolant. Just the corium that was slumped in the LP after the barrel failure was modeled. The initial and boundary conditions have been taken from the IVMR WWER1000 test case specifications, previously prepared from the integral calculation done with ASTECv2.0r2.

The calculation starts at 4910 sec. after the initiation of LB-LOCA and SBO. This is the time of barrel failure and melting, which leads to the slumping of nearly 190 t melted corium in the vessel LP. The composition of this corium is shown in Table 1. The main components of the corium are Stainless Steel, UO_2, ZrO_2 and Zr. The initial corium pool temperature is 2000 K.

Material	**Mass, t**
UO_2 from the CORE	85.9
Zr from the CORE	15.6
ZrO_2 from the CORE	17.1
Stainless Steel from the melted internal structures	69.84
Total mass	**188.44**

Table 1: Initial corium composition [11, 12]

The segmentation scheme of the reactor vessel's lower head is presented in Figure 3.
The RPV lower plenum was subdivided into 21 segments in height.
The RPV lower plenum was subdivided into 20 radial rings in the lateral direction.

The elliptical part of the vessel is realistically modeled mapping the WWER1000 reactor sited at the Kozloduy NPP. The elliptical part of the lower head vessel has been divided into 20 radial rings and 7 axial segments (a summary of 140 elements). The cylindrical part of the lower head vessel has been modeled as 20 rings and 14 axial segments (summary 280 elements). The elevation of 0.0 is assumed to be between the cylindrical part of the vessel and the cylindrical part of the lower head in the input (Fig. 3).

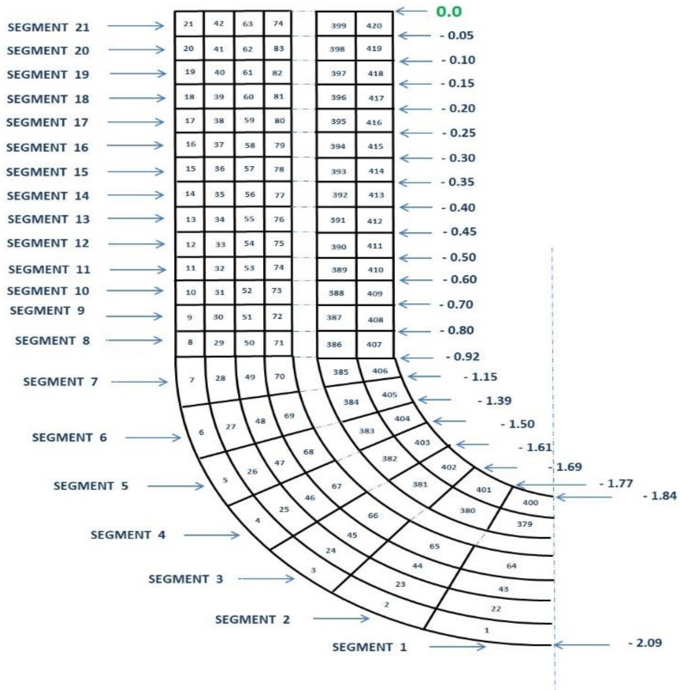

Figure 3: Nodalisation scheme of the WWER1000 reactor vessel lower head

The lower plenum geometry and the corium in it at the beginning of the calculation is shown in Figure 4. The radius of the cylindrical part of the lower head is 2.068 m. The thickness of the vessel wall is 25 cm.

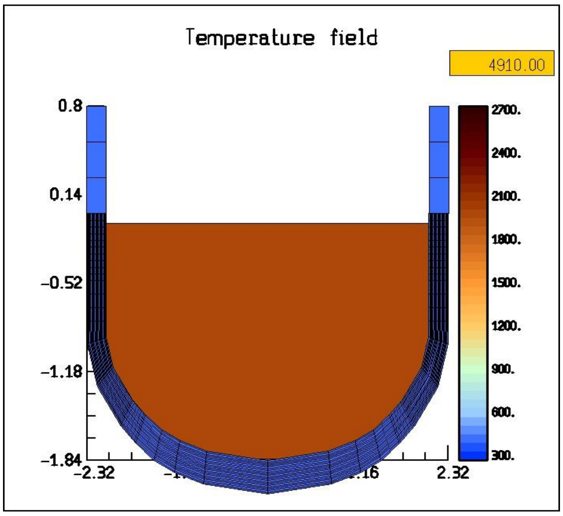

Figure 4: Lower plenum geometry and the corium in it at the beginning of the calculation

The decay heat generated in the corium due to fission product release is presented in Table 2. For a more realistic investigation, the table of the decay heat power was reduced by 20%, considering the release of volatile fission products.

Time, s	**Decay heat, W (per 1 kg of UO_2)**	**Time, s**	**Decay heat, W (per 1 kg of UO_2)**
4910	373.44	20000	240.08
5000	371.04	30000	215.12
6000	350.00	40000	200.40
7000	333.28	50000	190.16
8000	319.12	60000	182.24
9000	307.52	70000	175.12
10000	297.28	80000	168.96

Table 2: Decay heat table

In the input model, it has been implemented adequate external boundary conditions which simulate the outside LP vessel water cooling. The defined in the input model heat transfer coefficient between the vessel and the cooling water is 10 kW/(m^2*K). It was assumed that the outside water temperature is 110 ^{0}C. The external water cooling starts at the beginning of the simulation (at 4910 sec).

The vessel's outside pressure is assumed to be 1.5 bar

In the input, it has been activated phase separation model. Due to its activation corium in the lower plenum stratifies into a metallic layer at the top and an oxide layer at the bottom [18].

3. Results from basic calculation

The main results from the stand-alone calculation are depicted in Figure 5. There is presented in Fig. 5 the transient progression from 4910 sec. to 30000 sec., where it could be seen the lower plenum ablation in time and the changes in the temperatures in both layers.

The heat fluxes from the molten pool to the LP vessel wall inside the vessel are presented in Figure 6. The figure represents heat fluxes in height on the inside LP vessel wall. As the wall is discretized in segments the code calculates internal HF for each one of the segments.

Figure 7 shows the external heat fluxes (HF) from the LP vessel wall to the cooling water. Again there are represented external HF for each one of the segments from 1 to 21, as pointed in Fig. 3.

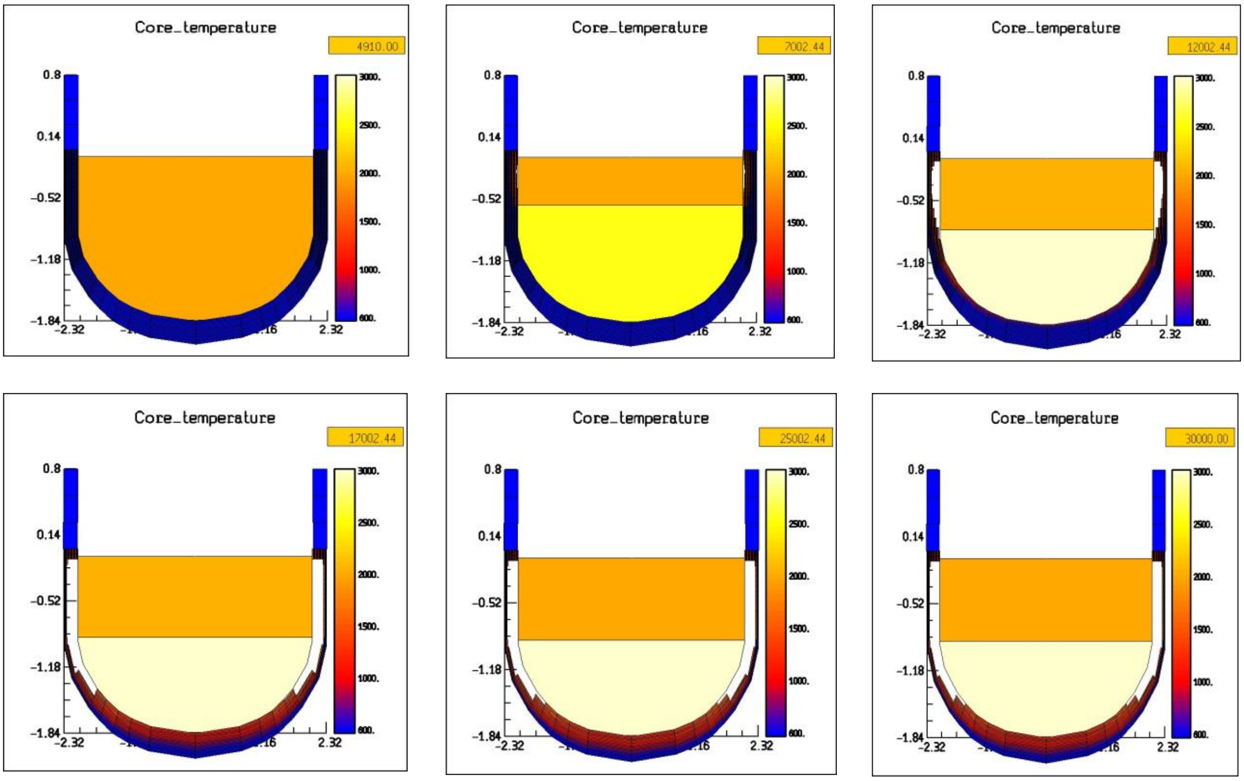

Figure 5: Transient progression from 4910 sec. to 30000 sec.

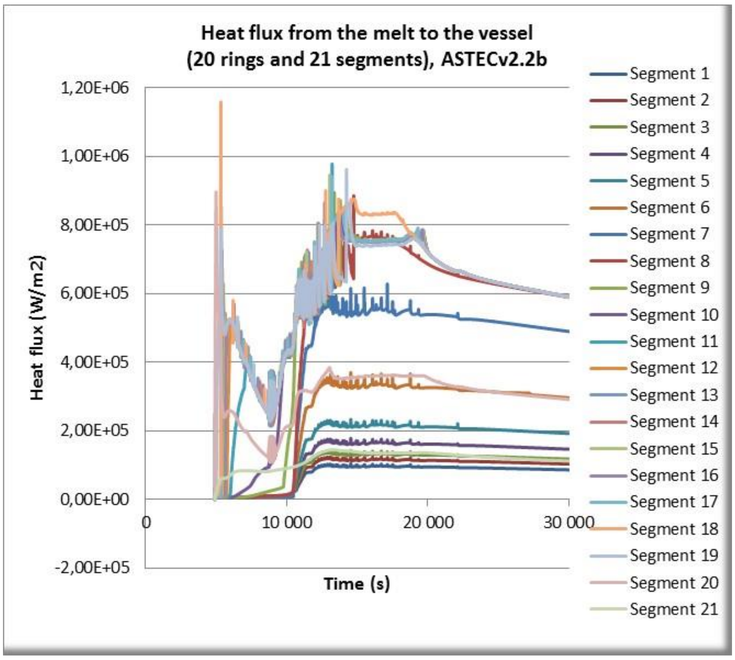

Figure 6: Heat flux from the corium pool to the internal surface of the LP vessel

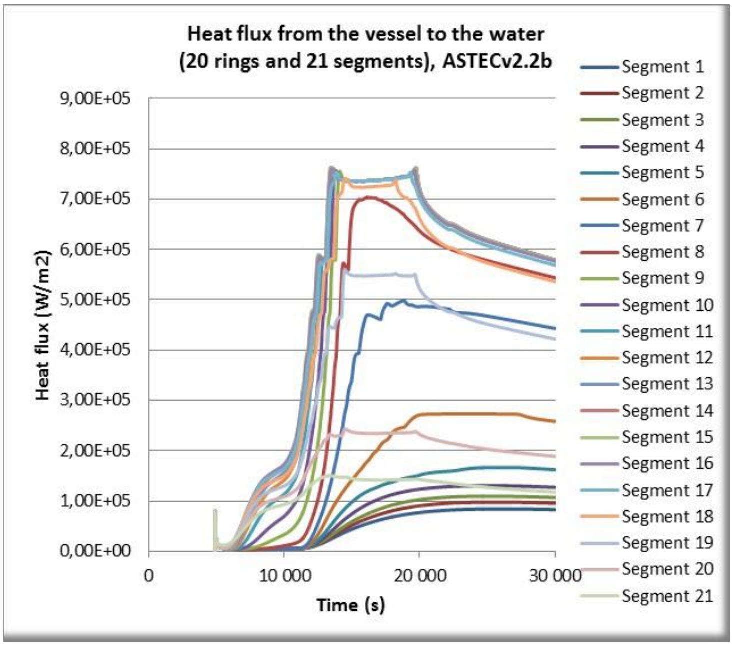

Figure 7: Heat flux from the external surface of the LP vessel to the outside cooling water

From the results presented above (in Fig. 6 and 7) for the internal and the external heat fluxes on the LP vessel wall it has been prepared diagram for maximum HF axial profiles along the vessel wall. These bounding curves in Figure 8 represent the maximal internal and external HF values reached during the simulation in each one of the segments.

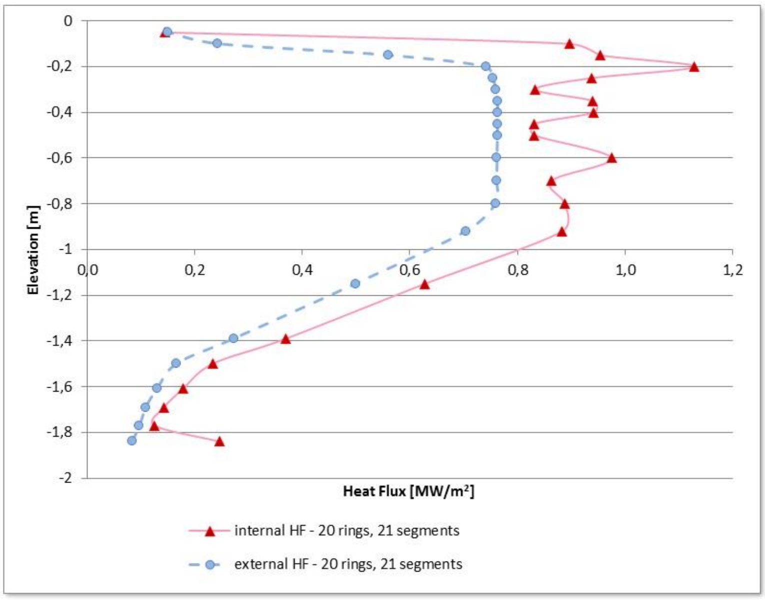

Figure 8: Bounding curves of maximal heat flux values reached in the segments

Looking at Figure 8 we ascertained that the absolute heat flux maximum of 1.1285 MW/m^2 in the basic stand-alone calculation happens at segment 18 (5322 s) and corresponds to the area between elevations -0.20 m and -0.15 m. So we could conclude that the most heat-loaded segment in this calculation is “Segment 18”.

The wall thickness of each one of the vessel segments is presented in Figure 9. The radial and axial dividing of the LP define vessel wall discretization in small elements called in the ASTEC code terminology "meshes". The segments of the LP vessel wall consist of 20 meshes (Fig. 3). As it seen in Fig. 3 internal meshes with numbers from 400 to 420 are in contact with the corium. After the meshes in contact with the corium are melted the rest meshes in the corresponding segment define the thickness of the LP vessel wall in this segment.

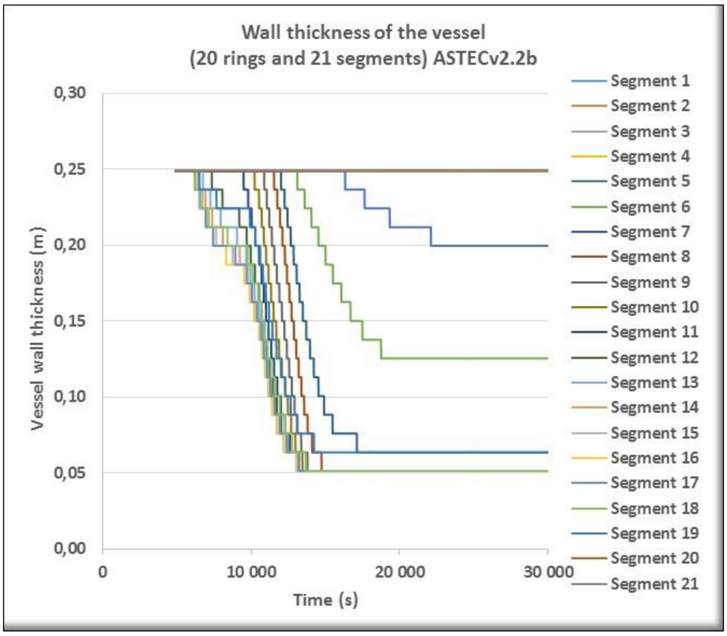

Figure 9: Vessel wall thickness in segments

In the next Figure 10 it is pointed the vessel LP shape at the end of calculation.

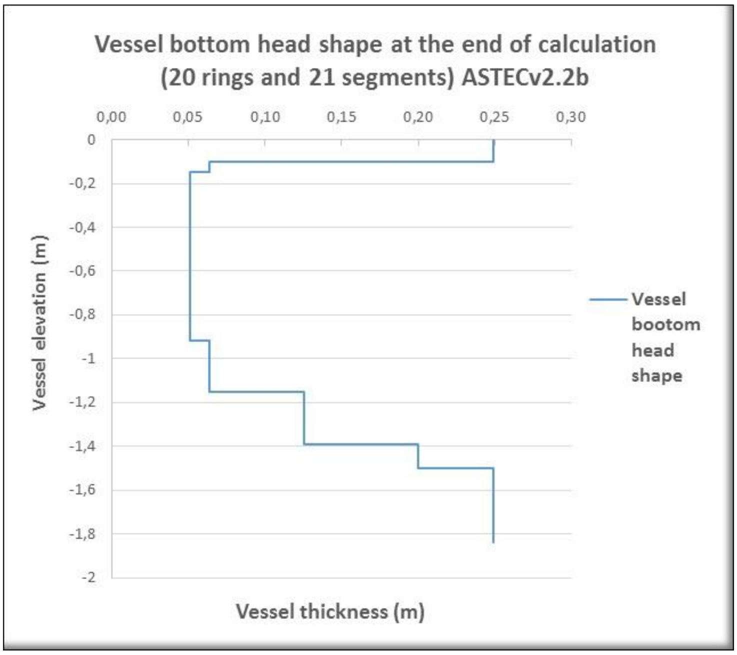

Figure 10: Vessel LP shape at the end of calculation

As is seen in Fig. 9 and 10 the minimal thickness (approximately 5.14 cm) is observed at segments 8, 9, 10, 11, 12, 13, 14, 15, 16, 17 and 18 at the end of calculation.

4. Uncertain input parameters in IVMR WWER1000 test case and choice of diapason of their deviation

It could be seen from the stand-alone calculation that the most heat-loaded segment of the vessel wall is „Segment 18". The final thickness wall in this segment is also minimal (5.14 cm). That's why the vessel thickness and the heat flux in Segment 18 are chosen as output parameters in the next uncertainty and sensitivity investigations done with SUNSET. The different values of inside vessel pressure and outside water temperature were investigated against these output parameters.

The maximal value of primary pressure in WWER1000 reactor type is 15.7MPa. To investigate the range of possible levels of primary pressure in case of severe accident it was chosen intermediate reference value of inside vessel pressure of 7.85 MPa and the deviation range of ±90%. In this case, inside vessel pressure varies from 14.915MPa to 0.785MPa (7.85bar). It could cover a significant part of the possible large and small break accidents with severe consequences (but not all of them).

The reference values of the input parameters in the IVMR WWER1000 test case and their accepted ranges are presented in Table 3.

№	**Parameter**	**Reference value**	**Deviation range (%)**
e1	The pressure inside the vessel	7.85 MPa	±90 %
e2	The temperature of the outside cooling water	110 ^{0}C	±20 %

Table 3: Uncertain parameters

5. Uncertainty analyses

Using the SUNSET/ASTECv2.2b coupling, 50 different "doncal" files containing 50 couples of uncertain input parameters selected at the Monte-Carlo method for Simple Random Sampling have been created. After that, using the "doncal" files, 50 ASTECv2.2b calculations of IVMR WWER1000 test case have been performed.

The results for vessel wall thickness of „Segment 18" (THIC18) are presented in Figure 11. As it is seen from Fig. 11 the maximal computed value of vessel thickness in "Segment 18" is 5,14 cm but the minimal computed value of vessel thickness is 2,67 cm.

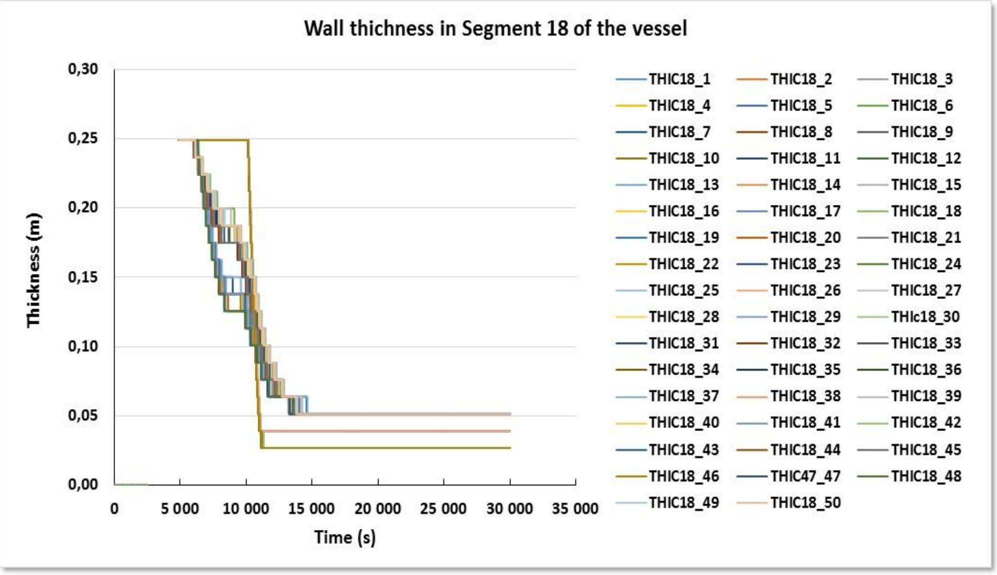

Figure 11: Wall thickness of Segment 18

The results for HF from the melt to the vessel in „Segment 18“ (HF18fi) are presented in Figure 12. As is seen from Figure 12 the maximal value of heat flux at the end (final equilibrium stage) of the calculation is 749899 W/m^2. The minimal computed value of heat flux at the end (final equilibrium stage) of the calculation is 574687 W/m^2.

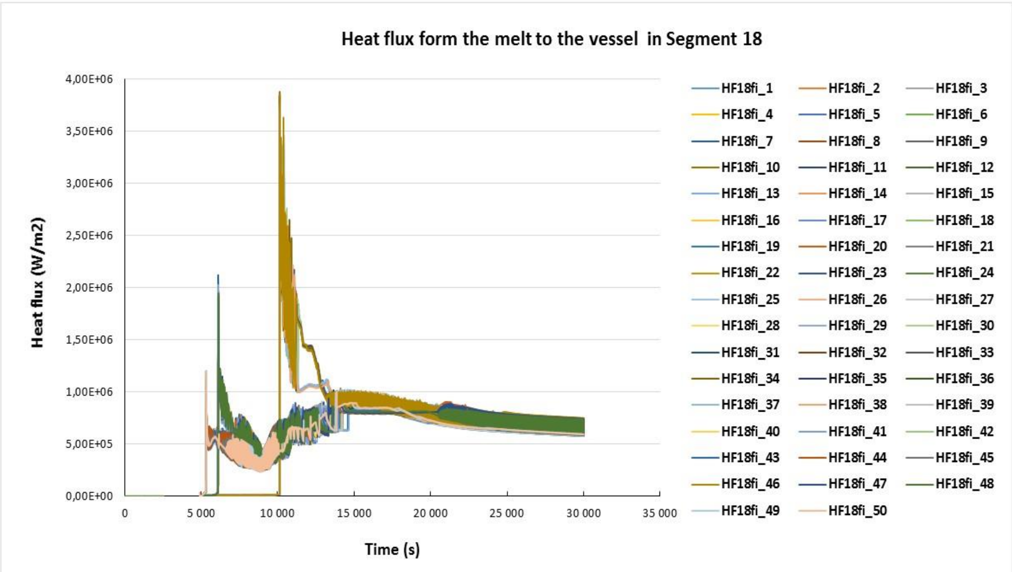

Figure 12: Heat flux from the melt pool to the LP vessel wall (Segment 18)

Table 4 represents the results from the uncertainty analyses and corresponds to those results presented in Figures 11 and 12. As a result of statistical analyses, the table gives information about the maximal, minimal, and average calculated values of the output variables, as well as information about the standard deviation, used to estimate the error due to the uncertainty.

Output variable	**average**	**standard deviation**	**min**	**max**
'Outputs_variable#1' THIC18	0.046213 (m)	0.009271552 (m)	0.0267 (m)	0.0514 (m)
'Outputs_variable#2' HF18fi	676537.4 (W/m^2)	70821.05 (W/m^2)	574687.0 (W/m^2)	749899.0 (W/m^2)

Table 4: Results from the classic statistical analysis for THIC18 and HF18fi

6. Sensitivity analyses

Using the SUNSET statistical module, it has been performed a sensitivity analysis of the investigated uncertain parameters (P_{inside_vess} and $T_{water\_outside}$) in the IVMR WWER1000 test case. In this sensitivity analysis, we use a simple regression method. We consider a couple of variables X (input variable or “regressor”) and Y (output variable). We consider X as a known and try to find out the function that expresses Y as a function of X. The output variables (Y_1 and Y_2) in our case are the thickness of the vessel wall in “Segment 18” (THIC18) and the HF from the melt to the vessel LP wall in “Segment 18” (HF18fi).

It has been used the “linear sensitivity module” to perform this sensitivity analysis. The least-squire method is used to determine the correlation coefficients and determination coefficients.

The correlation coefficients are presented in Table 5 and Fig.13.

	'Outputs_variable#1 – THIC18	'Outputs_variable#2 – HF18fi
e1	-0.6980405	0.6374212
e2	-0.007942254	0.01934724

Table 5: Correlation coefficients

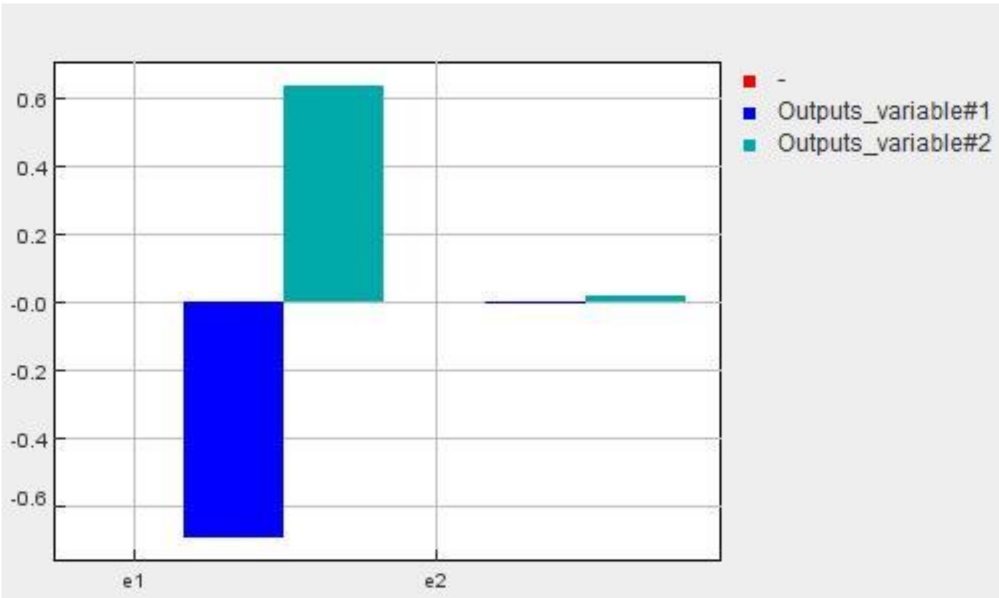

Figure 13: Correlation coefficients diagram

The correlation coefficients computed by SUNSET express the degree of influence of uncertain parameters (P_{inside_vess} and $T_{water\_outside}$) to the vessel wall thickness of "Segment 18" (Outputs_variable#1: THIC18) and to the HF on the "Segment 18" (Outputs_variable#2: HF18fi). If the correlation coefficient is positive the increase in the input variable X leads to an increase in the output variable Y. If the correlation coefficient is negative the increase in the input variable X leads to a decrease in the output variable Y.

As it is seen from Fig.10 the biggest influence on the THIC18 and HF18fi has the pressure inside the vessel (P_{inside_vess}). Inside vessel pressure (P_{inside_vess}) in range from 0.785 MPa to 14.915 MPa has a positive influence on the heat flux in "Segment 18" (HF18fi). An increase in inside pressure leads to an increase in the HF on "Segment 18". From the other side, P_{inside_vess} has a negative influence on the vessel thickness of "Segment 18" (THIC18). This means that the increase of this parameter leads to a decrease in vessel thickness in "Segment 18" (THIC18).

The temperature of the outside cooling water ($T_{water\_outside}$) in range from 88 ^{0}C to 132 ^{0}C has a negligible influence on THIC18 and HF18fi in comparison with parameter #1 (P_{inside_vess}). Outside cooling water temperature has a positive effect on the heat flux in "Segment 18" (a HF18fi) and negative effect on the vessel thickness in "Segment 18" (THIC18). This is because the cooling temperature rising slows down the vessel cooling.

The quality of a regression model is described by the coefficients of determination (R^2). This coefficient is the ratio between the variance explained by the regression model and the total variance of the response. The closer value of the determination coefficient to '1' shows that the linear regression fits better with the data.

The single determination coefficients are presented in Table 6 and in figures 14 and 15.

	'Outputs_variable#1 – THIC18	'Outputs_variable#2 – HF18fi
e1	0.4872605	0.4063058
e2	6.30794E-5	3.743158E-4

Table 6: Single determination coefficients

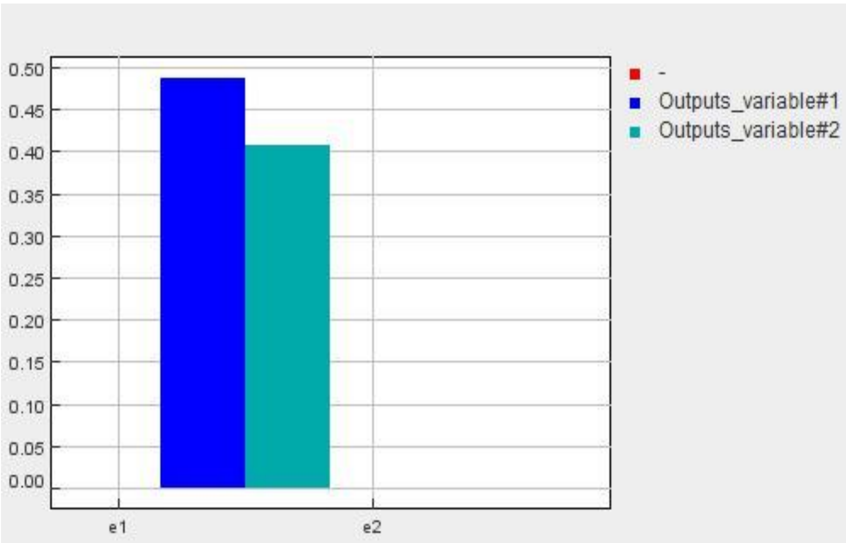

Figure 14: Single determination coefficients in liner sensitivity, accounting for the influence of P_{inside_vess} on the THIC18 and HF18fi

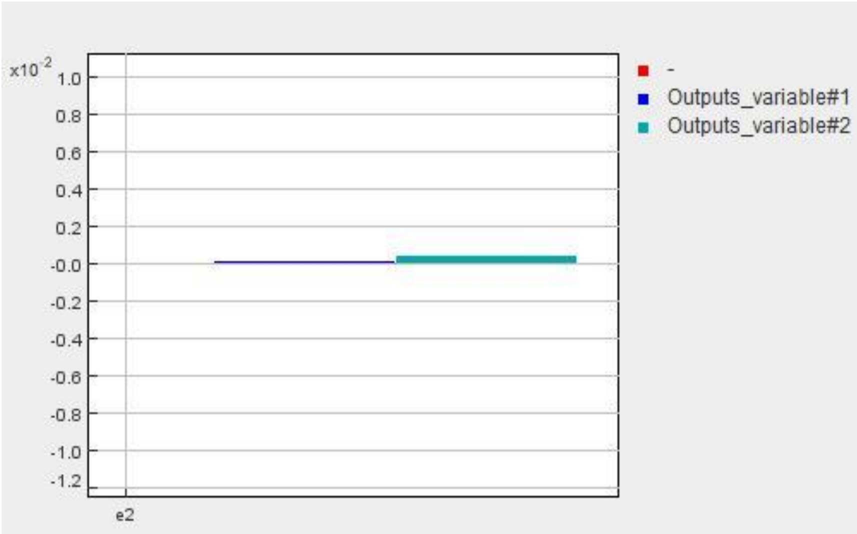

Figure 15: Single determination coefficients in liner sensitivity, accounting for the influence of $T_{water\_outside}$ on the THIC18 and HF18fi

7. Conclusions

The sensitivity evaluation by the SUNSET computer tool for the IVMR WWER1000 test case calculations shows that parameter#1 (P_{inside_vess}) is important for the calculation results. The other parameter#2 ($T_{water\_outside}$) has a considerably smaller influence.

This investigation shows also that pressure inside the vessel will effect considerably on the Risk 2 (Risk of excessive heat flux on the vessel wall) and on the Risk 3 (Risk of excessive vessel ablation), mentioned as the main risks for IVMR strategy applying in the Phenomena Identification and Ranking Table (PIRT) developed during the H2020 IVMR project.

The main conclusion is that further investigation of the inside vessel pressure influence will be appropriate and this parameter should be included as a parameter with great importance in the next extended PIRT development for the evaluation of IVMR phenomena.

Aknowledgement

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