Sensitivity Analysis of Ex-Vessel Corium Coolability Models in MAAP5 Code for the Prediction of Molten Corium–Concrete Interaction after a Severe Accident Scenario

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Abstract: A postulated progressing severe accident scenario has been simulated using MAAP5 code with the focus on ex-vessel cooling of molten corium in the reactor cavity. Various parameters associated with the prediction of molten corium–concrete interaction (MCCI) are identified. Accordingly, a sensitivity analysis is performed to assess the impact of these parameters on the predicted cavity floor erosion depth during this MCCI postulated accident. The sensitivity index of each variable parameter is determined using the Cotter indices method and Sobol’ indices method. At the early stage of the accident, the predicted cavity floor erosion depth is found to be highly sensitive to the downward heat transfer coefficient parameter with Cotter and Sobol’ indices of 94% and 50%, respectively. At the late phase of the accident, however, the cavity floor erosion depth becomes sensitive to melt eruption (Cotter index of 40%), water ingression (Cotter index of 13%), and particulate bed (Cotter index of 15%) parameters alongside the downward heat transfer coefficient parameter with Cotter and Sobol’ indices of 94% and 50%, respectively. At the late phase of the accident, however, the cavity floor erosion depth becomes sensitive to melt eruption (Cotter index of 40%), water ingression (Cotter index of 13%), and particulate bed (Cotter index of 15%) parameters alongside the downward heat transfer coefficient parameter with Cotter and Sobol’ indices of 94% and 50%, respectively. Thus, the sensitivity of the code’s predictions can be minimized by improving the physical models associated with these parameters. Moreover, the sensitivity indices of these parameters can be used by model developers to identify unimportant parameters in a bid to reduce the dimension of the problem with the aim of improving the current predictive capabilities to conduct MCCI-related safety analyses.

Keywords: severe accident; corium-concrete interaction; Sobol’ indices method; Cotter indices method; ablation of a cavity; MAAP5 code; sensitivity analysis

1. Introduction

In the event of an unmitigated severe accident scenario in the nuclear power plant that causes rupture of the reactor pressure vessel (RPV), molten corium can be expelled from the RPV to a dry or flooded concrete cavity or core-catcher located underneath the reactor core, depending on the ex-vessel mitigation strategy employed for the reactor design. As shown in Figure 1, in the case of a reactor that uses a concrete cavity, the molten corium can interact with the water pool in the cavity and subsequently with the concrete [1,2]. This phenomenon is known as molten corium–concrete interaction (MCCI) and it is very important for safety analysis of the reactor cavity and serves as a mitigation strategy for further exposure of radioactive materials to the environment through the basemat melt through (BMT) accident of the reactor cavity. This phase of the severe accident progression is characterized by many complex inter-dependent phenomena, such as particle bed formation during the transfer of corium to the water pool in the cavity, water ingression, melt eruption, and concrete ablation [3,4]. Since most of these phenomena are difficult to model mechanistically, most of the models used to represent them are parametric, and it, therefore, becomes necessary to perform a sensitivity analysis of the variable parameters in these models to identify important ones that influence the behavior
of the MCCI so that focused experimental study can be performed on such parameters to obtain a mechanistic model, hence greatly reducing the uncertainty in its prediction.

Several experimental studies have been performed over the years with a view to gather a better understanding and modeling of the molten corium–concrete interaction phenomenon. These experiments are either small-scale or large-scale and they are performed under transient or steady-state conditions using either simulant or prototypic corium to represent the core melt. For instance, at the early stage, BETA experiments [5] were performed using simulant in place of molten corium whereas contemporary experiments such as VULCANO [6], MACE [7], CCI [8], SURC [9] used prototypic corium. Other experiments such as LSL, LSB, and LSCRBR [10] were performed at Sandia National Laboratory, MEK-T1A [11] at Korean Atomic Energy Research Institute, and HECLA [12] at VVT Technical Research Center. The findings and data from these experiments have been leveraged over the years to model MCCI in several codes. Prominent among the codes are MAAP5, MELCOR [3,13], CORCON, CORQUENCH [4,14], ASTEC/MEDIC [15], MOQUICO [16], and so forth. Using these codes, various aspects of the MCCI have been investigated by researchers [3,4,17], which have revealed that large uncertainties still exist in the prediction of the MCCI by these codes and there is a need for rigorous analysis to narrow down the sensitive parameters in the model so that simple and focused experiments can be dedicated to their studies.

In light of this, using the MAAP5 code, sensitivity analyses of the controlling parameters in the MCCI model are performed in this study. This kind of analysis can provide modelers with interesting information that could be very useful for identifying unimportant variables so that the dimension of the problem can be reduced and simple dedicated experiments can be designed to enhance the model of the most sensitive parameters.

2. Description of Variable Parameters of MCCI Model in MAAP5 Code

In the MAAP5 code, many phenomena influence the progression of MCCI after a severe accident. Models for these phenomena have been developed using experimental observations and data. However, most of these models are parametric and therefore require fine-tuning of some parameters to achieve desired results, which introduces large uncertainty in the prediction by the code. For the sensitivity analysis, the detailed descriptions of the mathematical equations describing these phenomena are avoided in this study. This implies that the MCCI module of the MAAP5 code is treated as a black box with known controlling input parameters and the desired output parameter.

The controlling input parameters of MCCI and corium cooling models in the MAAP5 code can be divided into 4 categories: 1. Parameters associated with particle bed formation due to corium–coolant interaction during pouring of corium from the reactor pressure...
vessel to cavity 2. Parameters associated with heat transfer coefficient in the MCCI model 3. Parameters associated with the water ingression model 4. The parameter associated with the melt eruption model. These controlling parameters alongside their bounds and default values are summarized in Table 1.

### Table 1. Summary of the relevant controlling parameters of MCCI in MAAP5 code [18].

<table>
<thead>
<tr>
<th>Category</th>
<th>Parameter Name</th>
<th>Description</th>
<th>Lower Bound</th>
<th>Upper Bound</th>
<th>Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle bed formation due to Fuel–Coolant Interaction</td>
<td>IPBRB</td>
<td>Flag turning ON (1) or OFF (0) particle bed formation due to FCI.</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ENT0C</td>
<td>Ricou–Spalding jet entrainment coefficient.</td>
<td>0.025</td>
<td>0.06</td>
<td>0.045</td>
</tr>
<tr>
<td></td>
<td>EPSPB</td>
<td>The porosity of the particle bed.</td>
<td>0.26</td>
<td>0.53</td>
<td>0.4</td>
</tr>
<tr>
<td>Heat transfer coefficient in the MCCI</td>
<td>HTCMCR</td>
<td>Nominal downward heat transfer coefficient. The exponent is used to calculate the downward and sideward heat transfer coefficients.</td>
<td>500 W/m²K</td>
<td>$1 \times 10^5$ W/m²K</td>
<td>3500 W/m²K</td>
</tr>
<tr>
<td></td>
<td>CDU</td>
<td>Parameter for heat flux from a contiguous corium pool to water when IQDO = 0.</td>
<td>1</td>
<td>3</td>
<td>2.75</td>
</tr>
<tr>
<td>Water Ingression</td>
<td>IQDO</td>
<td>To specify a method to calculate dry-out heat flux from the top of a contiguous corium pool to water (if = 0: parametric method; =1: mechanistic method).</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>FCHF</td>
<td>Parameter for heat flux from a contiguous corium pool to water when IQDO = 0. Specifies permeability of materials cracking due to thermal stress of quenching when IQDO = 1.</td>
<td>0.0036</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>FIWNGS</td>
<td></td>
<td>1</td>
<td>5000</td>
<td>280</td>
</tr>
<tr>
<td>Melt Eruption</td>
<td>IMLTERP</td>
<td>Control flag to turn on melt eruption model. The coefficient in Ricou–Spalding entrainment correlation, which controls the efficiency of melt eruption generating particles.</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ENT0RB</td>
<td>Average diameter of particles entrained by off-gas.</td>
<td>$1 \times 10^{-4}$ m</td>
<td>$1 \times 10^{-2}$ m</td>
<td>$4 \times 10^{-3}$ m</td>
</tr>
</tbody>
</table>

An assessment of the impact of the controlling parameters of the MCCI model has been previously performed [19] to show how the change of parameters’ values within their minimum and maximum bounds affects the prediction of cavity floor erosion depth during the late phase of a severe accident scenario. However, the authors’ assessment in that study did not cover a detailed sensitivity analysis of these parameters in terms of a unified sensitivity index so that a precise conclusion can be drawn as to which parameter induces the greatest sensitivity in the prediction of the cavity floor erosion depth.

### 3. Simulation of a Severe Accident in a Zion-like Nuclear Power Plant

A Zion-like hypothetical nuclear power with a Westinghouse 4-loop PWR reactor coolant system and large dry containment is used in this study. The basic design information of the target plant is provided in Table 2. It is worth noting here that the parameter input file of this Zion-like reactor is provided alongside the MAAP5 code distribution. The nodalization of the reactor coolant system (RCS) of the plant is shown in Figure 2, in which the reactor pressure vessel (RPV) dome plate, upper plenum, core region, and lower plenum are four designated regions matching the number of RCS loops. Flows in each region are pressure-driven, and turbulent mixing is allowed between adjacent nodes (water-solid)
within the sub-regions. The pumps are operated in an asymmetric manner such that when one or more reactor coolant pumps (RCP) trip, other pumps can continue normal operation.

Table 2. Summary of the basic design parameters of the target plant.

<table>
<thead>
<tr>
<th>Descriptions</th>
<th>Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor type</td>
<td>PWR Westinghouse design</td>
</tr>
<tr>
<td>Power</td>
<td>3565 MW</td>
</tr>
<tr>
<td>Number of Steam Generator</td>
<td>4-Loop</td>
</tr>
<tr>
<td>Steam Generator type</td>
<td>U-tube</td>
</tr>
</tbody>
</table>

Figure 2. Nodalization of the RCS of the target plant for MAAP5 [20].

3.1. Simulation of Base (Default) Case

Using the MAAP5 code parameter file developed based on the Zion-like plant nodalization (see Figure 1), a severe accident scenario initiated by LBLOCA (large break loss of coolant accident) with 0.769 m² double-ended cold leg break is simulated for 24 h. The reactor was operated normally for about 3600 s prior to the initiation of LBLOCA accident. The reactor pressure vessel fails at about 14,600 s, and molten corium is discharged into the reactor cavity, which is in pre-flooded condition to about 10 m water elevation due to the operation of the safety injection and containment spray systems. The concrete material of the cavity floor assumed in this study is the Limestone Common Sand (LCS), and its properties are provided in the MAAP5 code. This forms the baseline simulation of the severe accident progression of the Zion-like nuclear power plant with a focus on the molten corium–concrete interaction because the default setting of the input control parameters (see Table 1) of the ex-vessel cooling of the molten corium and its interaction with the cavity concrete material are used. The sequence of events leading to the severe accident is summarized in Table 3.
Table 3. The sequence of events during a severe accident initiated by LB-LOCA.

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–3600</td>
<td>Normal operation of the power plant</td>
</tr>
<tr>
<td>3600</td>
<td>LB-LOCA by cold leg double-ended break, which is instantly followed by high-pressure injection (HPI) as the core becomes uncovered</td>
</tr>
<tr>
<td>3710</td>
<td>Start of low-pressure injection (LPI)</td>
</tr>
<tr>
<td>8847</td>
<td>Reactor in-core instrument failed</td>
</tr>
<tr>
<td>8930</td>
<td>Maximum core temperature is exceeded and the core meltdown</td>
</tr>
<tr>
<td>11,460</td>
<td>Relocation of core material to the lower plenum started with the lower head pool</td>
</tr>
<tr>
<td>14,694</td>
<td>Reactor pressure vessel failed by plug melt of instrumentation tube and corium relocated to the flooded cavity</td>
</tr>
<tr>
<td>84,740</td>
<td>Containment failed due to over-pressurization</td>
</tr>
</tbody>
</table>

Additionally, the evolution of some key properties (partial steam pressure, mole fraction of steam, and total mass of corium and eroded concrete materials) in the reactor cavity are displayed in Figure 3, clearly showing the landmark events of a cold leg break, reactor pressure vessel failure, and containment failure in the course of the accident progression. Likewise, the cavity floor erosion depth is shown in Figure 4, which seems to be arrested at about 62,500 s to the depth of about 0.4 m.

Figure 3. Evolution of some important parameters in the reactor cavity: steam pressure (top), the mole fraction of steam (middle), and mass of corium and eroded concrete (bottom).
Particulate bed formation occurs at a few stages of the accident progression, such as when the hot fuel collapses in the core, when the molten fuel interacts with the water at the lower plenum of the RPV, and when the molten corium interacts with water in the reactor cavity after the failure of the RPV. However, the particulate bed formation model in MAAP5 under consideration for sensitivity analysis in this study is the one developed for the particulate debris formed during the interaction of water with molten corium in the pre-flooded reactor cavity, as illustrated in Figure 5.

As stated earlier, the detailed description of the mathematical equations of these models and other models in this study are treated as a black box and not explicitly expressed. However, the focus is on the controlling input parameters of the model. For the particulate bed formation model, the parameter IPBRB controls whether or not the particles’ bed is formed on top of the corium pool when the corium jet is relocated from the vessel into the water pool in the reactor cavity. If it is set to 1, the mass that is stripped from the main corium jet due to corium and water interaction, when the jet is penetrating the water pool, is...
assumed to form the particles’ bed layer on top of a continuous corium layer. Subsequently, all associated heat transfer models of the particulate bed formation are activated. Due to some uncertainty, this phenomenon is assumed not to primarily occur during the late stage of the severe accident and is deactivated by the default model setup in MAAP5 code. However, if it is activated by setting IPBRB = 1, the cavity floor erosion rate is arrested at the depth of ~0.05 m, which is substantially smaller than when the phenomenon is absent, which is ~0.4 m as can be seen in Figure 6.

Figure 6. Effect of the particle bed formation on the cavity ablation.

Another important controlling parameter during the particulate bed formation is \( \text{ENT0C} \), which is the jet entrainment coefficient for the Ricou–Spalding correlation. It is used to calculate the particulation of a corium jet entering a water pool in the cavity. \( \text{ENT0C} \) is used to determine how large a fraction of the molten jet from the core will be entrained and become particulated as it pours through the water pool in the cavity. It is suggested that users assess the sensitivity of the results to the value of \( \text{ENT0C} \) using values of 0.045 (default), 0.025 (lower bound), and 0.06 (upper bound) for Level 2 sequences when there is a non-trivial amount of water in the pedestal or cavity when the vessel fails. It has the potential to impact the amount of steam generated in the containment and the cavity floor erosion depth, as can be seen in Figure 7. When the particle bed formation model is activated, the parameter EPSPB is also significant. This parameter represents the assumed porosity of the particulate debris bed with a default value of 0.4 with lower and upper bounds equal to 0.26 and 0.53, respectively. This parameter (EPSPB) does not have any substantial effect on the cavity floor erosion rate, as shown in Figure 7.

Figure 7. Effect of particle entrainment and porosity of the particulate debris bed.
3.3. Downward Heat Transfer Coefficient

After the completion of the relocation of the molten corium to the reactor cavity, crust layers are formed between the molten corium and concrete. Therefore, the heat energy is transferred from the molten corium to the crust layer, which in turn transfers it to the concrete. Thus, the amount of heat that is finally reaching the floor concrete depends on the downward heat transfer coefficient between the molten corium and crust layer.

The parameter HTCMCR is the nominal downward heat transfer coefficient for convective heat transfer from molten corium to the lower crust for corium–concrete interaction calculations. It is used to calculate the actual heat transfer coefficient. Since the value of HTCMCR may depend on the type of concrete, it is important to decide whether the concrete is basaltic (siliceous), Limestone common sand (LCS), or limestone concrete. In this study, LCS is assumed as the concrete material because it is the closest material to the concrete cavity of the APR1400 reactor, which is the ultimate target of this study and the corresponding default value of the HTCMCR is 3500 W/m²K with lower and upper bounds of 500 W/m²K and 100,000 W/m²K, respectively. As shown in Figure 8, the cavity floor ablation depth is very sensitive to this parameter (HTCMCR). When the HTCMCR is set to 100,000 W/m²K, an abrupt cavity ablation depth is observed at the early stage of the MCCI (see Figure 8). This is because the crust has not been substantially formed at this stage and all the generated heat is deposited on the concrete floor, causing the cavity floor to erode quickly. The ablation rate steadily slows as the accident progresses due to the evolution of the crust layer, which introduces some thermal resistance between the molten corium and the concrete.

![Figure 8. Effect of the downward heat transfer coefficient on the cavity ablation.](image)

Another controlling parameter that is associated with the downward heat transfer coefficient is the CDU. This parameter is the exponent used to calculate the downward and sideward heat transfer coefficients for convective heat transfer from molten corium to the lower side crust for corium–concrete interaction calculations. The default value of this parameter is 2.75 with lower and upper bounds of 1 and 3, respectively. The predicted cavity floor ablation depth is moderately sensitive to the value of the CDU. A higher value of the CDU results in a higher value of the downward heat transfer coefficient, which in turn leads to deeper cavity floor erosion depth, as can be seen in Figure 9.

3.4. Water Ingression Phenomenon

It was observed in MACE integral test that corium shrinkage occurred during crust formation and this caused defects/voids to appear in the solidified material (crust). Water filtrates down through the interstitial voids/defect (see Figure 10), enhancing the otherwise conduction-limited heat transfer process. The evidence of this process was found in...
the MACE experiment where the melt/water heat flux exceeded the realistic value for conduction across the crust formed [7]. The impact of the implementation of the model for this phenomenon in severe accident analysis code has been investigated in previous studies and found to significantly enhance the top surface boiling heat transfer and subsequently reduce the cavity floor erosion rate by about ~34% [3,21]. In light of the experimental evidence, the water ingestion model is activated by default in the MAAP5 code.

![Figure 9. Effect of the heat transfer coefficient exponent on the ablation rate.](image)

The controlling input parameter of the water ingestion model is IQDO. This parameter (IQDO) acts as the control flag for the mechanistic dry-out heat flux model. If IQDO = 0: the dry-out heat flux model is off, and if IQDO = 1: the dry-out heat flux model is on. The mechanistic dry-out heat flux model is a new model added in MAAP4.0.8 to more accurately assess the heat flux from a corium pool in the reactor cavity to the water pool on top. Previously, the heat flux from the corium to the water is evaluated by applying flat plate critical heat flux correlation. A model parameter FCHF is used to address the uncertainty in the critical heat flux because of cracking in the solidified corium and water ingestion through these cracks. The new dry-out heat flux model removes the necessity of using the model parameter FCHF. Instead, it calculates a cracking depth and a water ingestion depth (dry-out depth). The heat flux from the corium to the water is evaluated based on these depths. Figure 11 shows the substantial impact of mechanistic dry-out heat flux vis-a-vis plate critical heat flux correlation. Furthermore, FCHF is the flat plate critical heat flux (CHF) Kutateladze number. This number applies to the case of pool levitation of droplets from a heated surface in contact with an overlying water pool. The critical
velocity marks the transition from a churn-turbulent pool to a fluidized bed of droplets. The parameter (FCHF) has a significant influence on the predicted cavity floor erosion as shown in Figure 12, when FCHF has a default value of 0.1, and the lower and upper bounds have respective values of 0.0036 and 0.3.

![Figure 11. Effect of water ingression phenomenon on the ablation rate.](image)

![Figure 12. Effect of the parametric dry-out heat flux model on the ablation rate.](image)

In addition, FIWNGS is a modeling parameter in the mechanistic dry-out heat flux model (water ingression model). Before MAAP 5.02, this parameter was hard-wired in the code as 280.0. It reflects the permeability of different materials at cracking when quenched by water. For solidified corium material, it generally varies from several hundred to a few thousand. The effect of this parameter on the predicted cavity floor erosion is shown in Figure 13. A very high value of this parameter implies that the entire top crust is perforated, allowing water ingression into the crevices. This provides an alternative pathway of least resistance for the generated heat to evacuate through the top crust instead of going into the concrete. This way, the heat transfer to the concrete becomes significantly reduced, thereby arresting the ablation to a very minimal level.

3.5. Melt Eruption Modeling Parameter

Eruptions of particles have also been observed in the MACE experiment. This phenomenon is caused by the entrainment of melt by the concrete decomposition gases, thereby
transporting particles through the crevices in the crust into the top surface water coolant, as illustrated in Figure 14. The erupted melt can spread to form a particulate bed that is coolable in the form of a porous particle bed and high surface area volcanic eruption.

The parameter that activates the melt eruption model due to off-gas from concrete ablation is IMLTERP. If it is set to 1, off-gas is considered to entrain into the corium pool in the reactor cavity and carry molten mass with it. The molten mass then becomes added to the particle bed. Note that if IPBRB is set to 0, but IMLTERP is set to 1, a particle bed will not be formed when the corium jet is penetrating the water pool, but it can be formed when corium–concrete interaction starts and off-gas is generated. To completely disable the formation of the particle bed, both IPBRB and IMLTERP need to be set to 0.

The model for the melt eruption is turned on by default in the MAAP5 code. However, there is a large difference between the predicted cavity floor erosion when the melt eruption model is turned on and when it is off. This can be observed in Figure 15. Moreover, since the melt eruption is caused by melt entrainment by the decomposition gases, another parameter (ENT0RB), which is the coefficient in Ricou–Spalding entrainment correlation for the off-gas entraining corium process, greatly influences the predicted cavity floor ablation when the melt eruption model is activated (see Figure 16). The influence of the diameter of the entrained particle is also investigated. The parameter for the particle diameter is XDENTRB and its influence on the cavity ablation behavior is shown in Figure 17.
Figure 15. Effect of melt eruption phenomenon on cavity ablation.

Figure 16. Effect of entrainment coefficient on the cavity ablation.

Figure 17. Effect on entrained particle diameter on the ablation rate.
4. Sensitivity Analysis of the MCCI Modeling Parameters

The sensitivity analyses of the variable parameters of the MCCI models in the MAAP5 code are performed using two methods: Sobol’ indices method and the Cotter indices method. \( f(x) \) represents the mathematical model of the cavity floor erosion depth during molten corium–concrete interaction after a severe accident. The model \( M(x) \) depends on the input variables described by a random vector \( X = \{ x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11} \} \) with the elements of the input vector corresponding to the corium coolability model parameters IPBRB, ENT0C, EPSPB, HTCMCR, CDU, IQDO, FCHF, FIWNGS, IMLTERP, ENT0RB, and XDENTRB, respectively.

Using the curated data generated by MAAP5 code for different values of the controlling input parameters of the MCCI model, multiple linear regression relations are determined for the parameters (IPBRB, ENT0C, EPSPB, HTCMCR, CDU, IQDO, FCHF, FIWNGS, IMLTERP, ENT0RB, and XDENTRB) at 25,000 s, 50,000 s, and 75,000 s simulation times to calculate the cavity floor erosion depth, as illustrated in Figure 18. All the parameters are assumed to be uniformly distributed within their bounds (minimum and maximum values). The distribution has to be assumed uniform because only the limits of the parameters are known. Had the mean and variance values been known, then distributions such as lognormal and Gaussian distributions could also be used.

![Figure 18. The functional relation between the controlling parameters.](image)

4.1. Sensitivity Analysis Using Sobol’ Indices Method

The sensitivity analysis of the variable parameters influencing the prediction of cavity floor erosion depth is performed using the method proposed by Sobol’ [22]. Generally, the sensitivity analysis describes the effect of the variability of each input variable or their combinations on the variability of the model response, \( y = f(x) \). A black-box approach is employed for this kind of sensitivity analysis. This implies that the analysis is based only on the evaluation of the model response for some specified sample inputs, which are selected to optimize the output information about the model structure.

The sensitivity indices for the model \( f(x) \) are computed using the Sobol’ indices method, which is predicated on the expansion of the model into summands of increasing
dimensions. Following this expansion, the total variance of the model can be defined as the sum of the variances of the summands. In light of this, Sobol’ expansion is defined as:

\[ f(x) = f_0 + \sum_{i=1}^{N} f_i(x_i) + \sum_{1 \leq i < j \leq N} f_{ij}(x_i, x_j) + \ldots + f_{1,2,\ldots,N}(x_1, \ldots, x_N) \]  

(1)

with the assumption that the first term \( f_0 \) is constant and equal to the expected value of \( f(x) \) and the integration of the summands with respect to their own variables vanishes.

The expansion given by Equation (1) is then used to compute the variance decomposition of \( f(x) \), which is defined as:

\[ D = \int_{D_x} f^2(x) dx - f_0^2 \]  

(2)

and the partial variances are estimated as:

\[ D_{i1,\ldots,is} = \int_0^1 \ldots \int_0^1 f_{i1,\ldots,is}^2(x_{i1}, \ldots, x_{is}) dx_{i1}, \ldots, dx_{is} \]  

(3)

where \( 1 \leq i_1 < \ldots < i_s \leq N; s = 1, \ldots, N \) since the integrals of the summands with respect to their own variables are zero. The sensitivity indices can be naturally defined from the variance decomposition as:

\[ S_{i1,\ldots,is} = \frac{D_{i1,\ldots,is}}{D} \]  

(4)

This definition (Equation (4)) represents the relative contribution of each group of variables to the total variance. Thus, the Sobol’ total variance of the input variable \( X_i \) is denoted by \( S^T_i \), and this is defined as the sum of all the Sobol’ indices involving this variable, as can be seen in Equation (5).

\[ S^T_i = \sum_{\{i_1,\ldots,is\} \ni i} S_{i1,\ldots,is} = 1 - S_{\sim i} \]  

(5)

where \( S_{\sim i} \) is the sensitivity index of all the variables excluding variable \( X_i \).

The variances defined in Equation (2) and Equation (3) can be estimated by Monte Carlo (MC) simulation. Detailed mathematical descriptions of the Monte Carlo estimators can be found in previous literature [22–24]. In addition, polynomial chaos expansion (PCE) and canonical low-rank approximation (LRA) metamodel are also used to compute the Sobol’ indices of the cavity floor erosion model in this study for comparison with Monte Carlo simulation. The sensitivity analyses are performed using UQLAB sensitivity analysis module [25], in which all the aforementioned techniques are implemented.

At the early stage of the severe accident, when the simulation time is 25,000 s, Sobol’ indices calculated by Monte Carlo (MC), Polynomial Chaos Expansion (PCE), and canonical Low-Rank Approximation (LRA) show that the downward heat transfer coefficient parameter (HTCMCR) is the most sensitive of the variable parameters, as shown in Figure 19a. This is because the ablation of the cavity floor at this stage of the accident is primarily determined by the interaction of molten corium with the concrete through the convection heat transfer. As the accident progresses, when the simulation time is 50,000 s, the sensitivity analysis reveals that melt eruption (IMLTER), water ingression (IQDO), and particle bed formation (IPBRB) becomes significant alongside the downward heat transfer coefficient (HTCMCR) but HTCMCR is still the dominant parameter, as can be seen in Figure 19b.

At the late phase of the accident progression when the simulation time is 75,000 s, the Sobol’ index of the melt eruption parameter (IMLTERP) becomes slightly higher than that of HTCMCR, as shown in Figure 19c. This is because the impact of melt eruption is enormous and it is expected at the late phase when enough steady concrete decomposition gases are being generated.
It is important to state here that the sensitivity induced on the cavity floor erosion prediction by the controlling parameters that are either turned on or off, such as IPBRB, IQDO, and IMLTERP, can be attributed to the uncertainty or probability of occurrence of the phenomena represented by these parameters. Each of these parameters (IPBRB, IQDO, and IMLTERP) has associated controlling parameters as well. For instance, when
IQDO is turned off, the parameter FCHF is used to control the flat plate critical heat flux correlation that is used to predict the heat flux from corium to the water pool with the assumption that water ingestion does not occur. Moreover, when IQDO is turned on (meaning water ingestion occurs), FIWGS is a modelling control parameter in the mechanistic dry-out heat flux model that captures the water ingestion phenomenon. The associated controlling parameters of IPBRB and IMLTERP have been previously discussed in Sections 3.2 and 3.5, respectively. As can be seen in Figure 19, the Sobol’ method could not clearly capture the relative sensitivity indices of the associated parameters of the IPBRB (particle bed formation), IQDO (water ingestion), and IMLTERP (melt eruption) due to dependency issues.

4.2. Sensitivity Analysis Using Cotter Indices Method

To overcome the dependency issue of the Sobol’ indices method, the Cotter method is additionally used to analyse the MAAP5 data to better capture the sensitivity of the cavity floor ablation depth to the associated parameters of IPBRB (ENT0C, EPSPB), IQDO (FCHF, FIWNGS) and IMLTERP (ENT0RB, XDENTRB), which indicate phenomena with some uncertainties and therefore can be turned on or off without assigning any values. The Cotter method [26] is straightforward and high-speed, which permits the ranking of the input parameters. The method applies to any situation irrespective of the dependence between the input variables. Considering an input vector \( X \) (as defined above), in which each input variable \( X_i \) it is assumed to vary in a known interval indicated by its low and high levels \( X_i \in [x_i^-, x_i^+] \). Using this definition, a systematic fractional replicate design is performed such that \( 2M + 2 \) model is evaluated following the steps below.

- First run with all variables at their low levels \( (y_0 = M(x_1^-, \ldots, x_M^-)) \).
- \( M \) runs at low levels, switching one variable at a time to its high level \( (y_i = M(x_1^-, \ldots, x_i^+, \ldots, x_M^-)) \), \( i = 1, 2, \ldots, M \).
- \( M \) runs at high levels, switching one variable at a time to its low level \( (y_i = M(x_1^+, \ldots, x_i^-, \ldots, x_M^+)) \), \( i = 1, 2, \ldots, M \).
- Last run with all variables at their high levels \( y_{2M+1} = M(x_1^+, \ldots, x_M^+) \).

Afterward, the significance of the variables is estimated as the Cotter index, which is defined below:

\[
I_{\text{Cotter}}(i) = |C_0(i)| + |C_e(i)| \tag{6}
\]

where \( C_0(i) \) and \( C_e(i) \) represent the expectation of the significance of the odd and even order effects, respectively, of the input variable \( X_i \) and these terms are defined as shown in Equations (7) and (8).

\[
C_0(i) = \frac{1}{4}[(y_{2M+1} - y_{M+i}) + (y_i - y_0)] \tag{7}
\]

\[
C_e(i) = \frac{1}{4}[(y_{2M+1} - y_{M+i}) - (y_i - y_0)] \tag{8}
\]

The input variables (IPBRB, ENT0C, EPSPB, HTCMCR, CDU, IQDO, FCHF, FIWNGS, IMLTERP, ENT0RB, and XDENTRB) are assumed to be uniformly distributed with low and high levels \( (x_i^+) \) matching the lower and upper bounds of the corresponding input variables (see Table 1).

Just like the Sobol’ indices method, the Cotter method also shows that the variability of the predicted cavity floor erosion depth is dominated by the parameter HTCMCR for the downward convection heat transfer coefficient between the molten corium and the crust at the early stage of the MCCI as shown in Figure 20a. As the accident progresses, water ingestion (IQDO) and melt eruption (IMLTERP) phenomena come into play as they induce significant sensitivity to the cavity ablation rate (see Figure 20b relative to Figure 19a) in addition to the downward convection heat transfer phenomena. At the late phase of the accident, the melt eruption parameter (IMLTERP) becomes the dominant inducer of variability on the cavity floor ablation depth, as can be seen in Figure 20c.
Figure 20. Cotter sensitivity indices of the MCCI controlling parameters in MAAP5 code: (a) 25,000 s, (b) 50,000 s, and (c) 75,000 s simulation time.
In addition, the parameters (ENT0C and EPSPB) that are associated with the particle bed formation parameter (IPBRB) have an infinitesimal influence on the sensitivity of the predicted cavity floor erosion depth by the MCCI model. This implies that the prediction of the ablation depth is not sensitive to these associated parameters, as can be seen in Figure 19, which can also be corroborated by Figure 7 above. In contrast, the parameters (FCHF and FIWNGS) that are associated with the water ingression parameter (IQDO) and the parameters (ENT0RB and XDENTRB) associated with the melt eruption parameter (IMLTERP) induce a significant sensitivity to the predicted ablation rate by the MCCI model as shown in Figure 20.

5. Conclusions

The prediction of ex-vessel cooling of molten corium in the reactor cavity has been presented in this article, showing all the variable parameters influencing the behavior of cavity floor ablation. The prediction of the cavity floor erosion depth is highly sensitive to the downward heat transfer coefficient at the early stage of the accident. At the late phase of the accident, the floor erosion depth becomes sensitive to the melt eruption, water ingression, and particle bed formation parameters alongside the downward heat transfer coefficients. The melt eruption parameters become dominant at this stage. Thus, to minimize the sensitivity of the floor erosion depth to these parameters, the models associated with these parameters should be improved from parametric models to mechanistic models. Moreover, the sensitivity indices of the MCCI controlling parameters in the MAAP5 code presented in this study can also be used by the model developer to isolate unimportant variable input parameters, hence reducing the dimension of the problem. In turn, this would allow for future research studies on this topic to focus only on those parameters that induce significant sensitivity to the predicted cavity floor erosion depth.

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References
1. Amidu, M.A.; Olatubosun, S.A.; Ayodeji, A.; Addad, Y. Severe accident in high-power light water reactors: Mitigating strategies, assessment methods and research opportunities. Prog. Nucl. Energy 2022, 143, 104062. [CrossRef]
2. Addad, Y.; Amidu, M.A. Numerical prediction of slug flow boiling heat transfer in the core-catcher cooling channel for severe accident mitigation in nuclear power plant. Nucl. Eng. Des. 2022, 393, 111796. [CrossRef]