Proceedings of HTR 2018
Warsaw, Poland, October 8-10, 2018
Paper HTR 2018-618

# Loss of Forced Cooling accident analysis of HTR-PM using MELCOR 2.2 Code

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**Abstract –** *This MELCOR 2.2 severe accident was used to study two accident scenarios in the Chinese high temperature reactor HTR-PM. A model of the reactor core, thermal insulator and metal structures, reactor pressure vessel and the residual heat removal system was created using the information from the open source literature. A steady state calculation was performed and used as an initial condition for the simulation before the accident sequence commenced. In pressurized loss of forced cooling accident the coolant helium flow was decreased to zero and the reactor was shut down. A natural convective flow was established in the pebble bed core due to the high pressure in the primary system and the peak fuel temperature during the accident was 1438 K. In de-pressurized loss of forced cooling accident the pressure of the primary system is lost causing the coolant flow to stop and reactor to shut down. The heat was removed from the core mainly by thermal radiation and heat conduction leading to the peak fuel temperature of 1730 K. The results were compared to previously published simulation data obtained using a THERMIX code. The peak fuel temperature results didn't differ significantly between the both simulations, with the main differences probably caused by the uncertainties in the input parameter used in this study. In the future work, MELCOR code is planned to be used in the simulation of fission product release and transport in the pebble bed high temperature reactors during accident normal operation and in accident conditions.*

## I. INTRODUCTION

MELCOR is an integral computer code developed by the Sandia National Laboratories for modeling severe accidents in nuclear power plants [1]. The main focus of MELCOR is on the simulation of accidents in light water reactors, but since the code version 2.1, also accident scenarios in High Temperature Gas-cooled Reactors (HTGRs) can be considered. The current version of the code contains models for both prismatic block and the pebble bed fueled HTGR designs. The HTGR specific models contain for example the radial heat conduction in the pebble bed core and the possibilities of using helium coolant as well as graphite moderators. The code also includes model for fission product release from the fuel elements during normal operation and in accident conditions of the HTGR [2]. In the previous investigation, Corson [3] conducted an extensive study on Pressurized and De-pressurized Loss of Forced Cooling (PLOFC and DLOFC) accidents in the South African PBMR-400 design using the MELCOR 2.1 code. Also, a previous modified version of the MELCOR code has been used for example on an analysis of air ingress accident in a pebble bed reactor [4].

In this study, MELCOR 2.2 code was used to simulate pressurized and de-pressurized loss of forced flow accidents in the Chinese pebble bed reactor HTR-PM. Previously, Zheng et al. [5] have conducted an analysis on the same accidents in HTR-PM using THERMIX code. THERMIX is a thermohydraulics steady state and transient code for pebble bed reactor primary circuit, including a neutron point kinetics and graphite corrosion models. We will compare our result of the fuel temperature in accident condition to Zheng et al. and identify the major differences and their possible causes.

## II. MODELING WORK

The model of the HTR-PM was constructed using the description found from the open source literature [5-8]. In case the required information was not discovered for the HTR-PM, details from the HTR-10 [9] or from other HTGR pebble beds were used [10].

The preparation of the input was conducted following the example of Corson [3] and Young [2]. Following the work of Corson, the MELCOR model of the HTR-PM pebble bed reactor core model contains 8 rings and 29 axial levels. Figure 1 shows a schematic of the MELCOR model of the HTR-PM core. The pebble bed is circled by a side, top and bottom graphite reflectors which is followed by a carbon brick thermal insulator. The bottom carbon brick was modeled as a core support structure (at the axial level a1) and the top and side carbon bricks as Heat Structures (HS). The cold gas enters the reactor through the riser channel, located at the side reflector in r8 radial section, from where it enters to the top void section of the core (axial level a28), devoid of the fuel pebbles. After reaching the bottom of the pebble bed, the hot helium exits the reactor to the hot helium plenum through coolant channels located in the bottom reflector. Porosity of the pebble bed was assumed to be 0.39 [10]. This value was also being used in the open literature as a uniform porosity for the simulation of HTR-PM [8]. A flat lower head model was used in the simulation of the pebble bed (Fig. 1).

Due to lack of details on the geometry of helium channels, control rod channels and the hot and cold plenums situated in the reflector, the bottom and side reflectors were assumed to be porous with 20 % porosity. This assumption was also used in the work of Corson [3] for on the PBMR benchmark [10], and in the simulation work it has an effect on the masses of the reflector graphite and thus on the heat transfer taking place in these volumes. Additionally, adiabatic boundary conditions were assumed for the reactor bottom and top boundaries similar to the work of Corson since the detailed description of the top and bottom structures of the reactor were not available in the literature references.

The equation for specific heat capacity ($C_p$) of the reflector graphite and the carbon brick in the HTR-PM were obtained from [5]:

$$C_P = 0.645 + 3.14 \times 10^{-3}T - 2.809 \times 10^{-6}T^2 + 0.959 \times 10^{-9}T^3, T \leq 1200\ °C \qquad \text{(eq. 1)}$$

Thermal conductivity ($\lambda_g$) of graphite [9] is defined as:

$$\lambda = 1.15(1 - 1.084\left(\frac{T}{1000}\right) + 0.743\left(\frac{T}{1000}\right)^2 - 0.213\left(\frac{T}{1000}\right)^3, T < 1700\ °C \qquad \text{(eq. 2)}$$

Thermal conductivity of the carbon brick ($\lambda_{CB}$) is obtained from [5]:

$$\lambda = 0.05 + 0.03 \times 10^{-3}T,\ T \leq 1200\ °C \qquad \text{(eq. 3)}$$

The specific heat capacity and thermal conductivity for the core barrel and RPV were obtained from the HTR-10 description [9] since no reference for the HTR-PM was found from the open literature. The values of the specific heat capacities and thermal conductivities of different materials are summarized in Table 1.

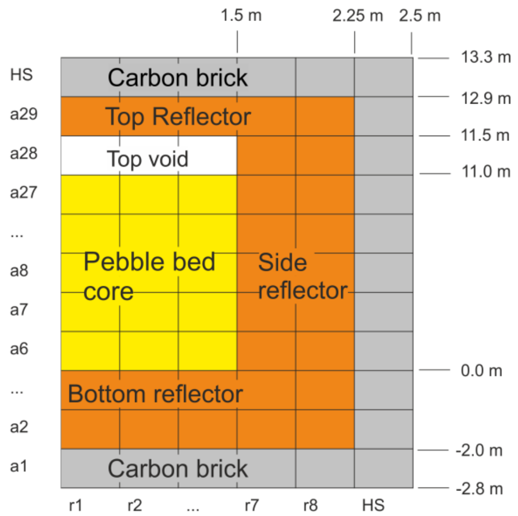


Fig. 1: Schematic of the MELCOR model of the HTR-PM core.

Table 1: Material properties.

| | Specific heat capacity $C_p$ [J/m$^3$/K] | Thermal conductivity [W/m/K] |
|---|---|---|
| Reflector graphite | (eq. 1) | (eq. 2) |
| Carbon brick | (eq. 1) | (eq. 3) |
| Core barrel (SS) | 471 | 37 |
| RPV (SS) | 471 | 37 |

For determining the heat transfer coefficient on at the surface of a fuel element in the pebble bed core, a German safety guide KTA3102.2 rules has been commonly used in the simulations of HTGR pebble bed reactors [5]:

$$Nu = 1.27\frac{Pr^{1/3}}{\varepsilon^{1.18}}Re^{0.36} + 0.033\frac{Pr^{1/2}}{\varepsilon^{1.07}}Re^{0.86} \quad \text{(eq. 3)}$$

In (eq. 3), $\varepsilon$ is the porosity of the pebble bed. Re is the Reynolds number Pr the Prandtl number and Nu the Nusselt number. However, in MELCOR the correlation for the Nusselt number in a pebble bed can only be inserted in a form:

$$Nu = aRe^{b}Pr^{c} \quad \text{(eq. 4)}$$

In this work, we followed the example of Corson, where the constants a and b for correlation (eq. 4) were obtained by curve fitting the KTA rule (eq. 3) data at Re range 10000-20000. Re number of approximately 10000 is also a realistic value for the HTR-PM pebble bed in a normal operation conditions. The Prandtl number remains almost unchanged in the conditions of the pebble bed reactor and thus the constant $c$ can be assumed to be 0.

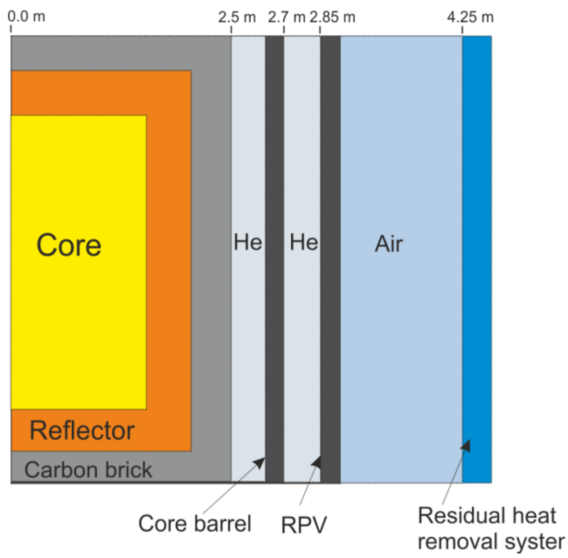


Fig. 2: Schematic of the MELCOR model of HTR-PM.

Figure 2 shows the schematic of the part of the HTR-PM where the MELCOR model was created in this work. The carbon brick insulator is encased by cylindrical core barrel (CB) and reactor pressure vessel (RPV). Both of these structures are separated by a helium gas space. The RPV thickness is 0.131 m [5] and the core barrel thickness was estimated to be 0.05 m. Residual heat removal system (RHRS) is a water cooling panel and it is located outside the RPV, 4.25 m from the reactor core center. The RHRS is set to a constant temperature of 343 K, which is the average temperature of the water cooling panel, reported in [5]. In MELCOR, CB, RPV and RHRS were modeled as heat structures and the material of the CB and the RPV was assumed to be stainless steel. The volume between the RPV and the RHRS consists of air. The heat is transferred from the core barrel to RHRS mainly through thermal radiation and heat conduction. The view factors between the carbon brick, core barrel, RPV and the RHRS were determined following the procedure described by Corson. The emissivities of the CB, RPV and RHRS were set to 0.9 [5]. The convective heat transfer by natural convective flows in the He gaps outside the reactor core or in the air gap was not modeled in this work.

Reactor power was extracted from the data from a previous work conducted in PSI [11], where the pebble burnup in the HTR-PM was investigated. The core power distribution was obtained from simulation using a 3D continuous-energy Monte Carlo code Serpent 2. In the simulations, the pebble bed containing fuel with an average burnup. The obtained power distribution was inserted to the MELCOR model and is shown in Fig.3. Decay power was obtained from the OECD PBMR benchmark [10] and is shown in Fig. 4. It is calculated for an equilibrium core without any burn-up specified in the benchmark description. Even though the decay power curve was not originally attained to a HTR-PM, it is however very similar to the one used by Zheng et al. and depicted in [5], representing a decay power of a fuel pebble after 15 passes in the HTR-PM.

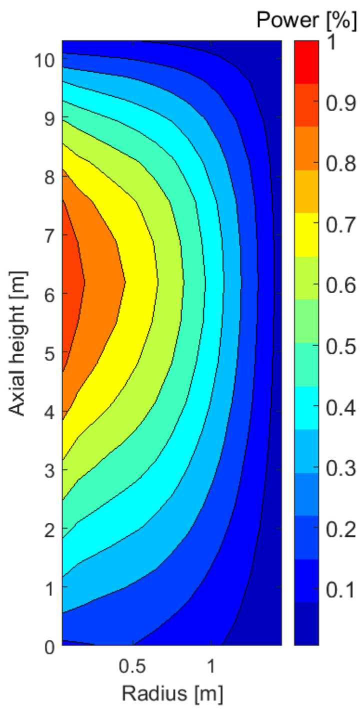


Fig. 3: Power distribution in the HTR-PM core.

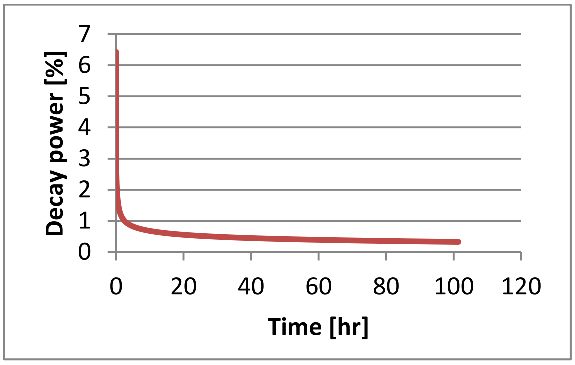


Fig. 4: The decay power used in the MELCOR model [10].

### *II.A. Initialization of the normal operation conditions*

Following the work of Corson, the coolant inlet and outlet are modeled as a steady source and sink of the helium gas. Due to this, the He balance in the primary circuit or the operation of the steam generator will not be simulated, which however are not important since the focus of this work is to investigate the reactor heat transfer during the accident conditions where the coolant flow has been lost.

Before the accident simulations, normal operation conditions were achieved by running the simulation for 5000 s. During this time, steady pebble bed and reflector temperatures were reached. In normal operation of the reactor, the helium mass flow rate through the reactor core is 96 kg/s. The inlet He temperature is 523 K and the pressure of the reactor is 7 MPa.

### *II.B. Pressurized loss of forced cooling accident*

In the pressurized loss of forced cooling (PLOFC) accident, the coolant flow is lost due to, for example, malfunction in a helium blower. In the simulation at time 0 s, the He flow at the inlet is reduced to 0 kg/s in 30 seconds, after which the reactor receives a trip signal. After the SCRAM, the reactor power is reduced to decay power, shown in Fig. 4. The primary circuit is assumed to remain intact, resulting on the pressure to remain in 7 MPa.

For the PLOFC accident, new parameters were obtained for the curve fit (eq. 4) since the average Re number in PLOFC conditions is much lower (~100).

### *II.C. De-pressurized loss of forced cooling accident*

In a de-pressurized loss of forced cooling accident (DLOFC), the pressure of the reactor is lost due to break in the primary circuit. The pressure is reduced to 0.1 MPa in approximately 20 s, resulting also a loss of coolant flow and a reactor SCRAM, similar to PLOFC accident.

## III. RESULTS AND DISCUSSION

### *III.A. Normal operation*

Figure 5 shows the temperature distribution in the pebble bed during a normal operation of a HTR-PM, obtained from the MELCOR simulation. The fuel elements reach their maximum temperature 1174 K at the center of the pebble bed at the lowest level of the core containing fuel elements (a6, r1). Zheng et al. didn't report the steady state temperature results in [5]. However, Auwerda in [8] presents a figure of a THERMIX simulation result of a solid temperature in HTR-PM. The exact temperature values are not reported, but the temperature distribution is qualitatively very similar to the one obtained from our MELCOR simulation for the pebble bed core. Also, pebble bed temperature at the bottom center of the core, indicated by the figure, is near 900 °C which corresponds to 1173 K.

He coolant temperature entering the reactor was set to 523 K. As it reached the outlet at the bottom of the reactor, its temperature has increased to 1024 K or 751 °C, which is very close to the nominal outlet coolant temperature of the HTR-PM [5].

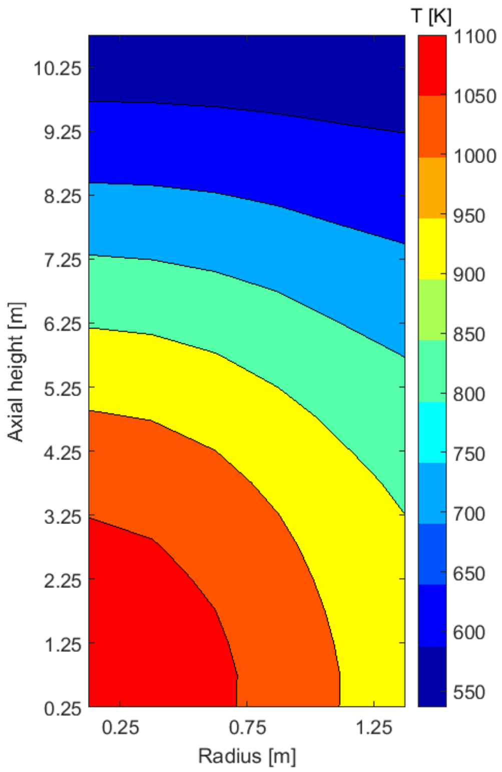


Fig. 5: Average fuel element temperature in the pebble bed core during normal operation.

*III.B. Loss of Forced cooling accidents*

The simulations time for both accidents was 150 hours. During this time, the maximum fuel temperature was reached, and followed by its steady decline.

In PLOFC accident, the fuel reached its highest temperature (1438 K) when approximately 12.5 hours have passed from the loss of forced cooling and the reactor shutdown. The temperature profile of the pebble bed during the max fuel temperature (12.5 h) is shown in Fig. 6. It shows how, compared to the normal operation (Fig. 5), the location of the temperature maximum has moved at the top of the pebble bed (a26, r1 in Fig. 1). Due to pressure remaining high in the primary circuit during the PLOFC accident conditions, the buoyancy is strong enough to lift the hot He gas at the top of the pebble bed. This causes natural circulation to occur in the reactor core and in turn increases transfer of decay heat from the reactor. This effect is well known in the HTGRs and has been well documented, for example in [3,5,12]. The natural circulation in the pebble bed during the PLOFC is shown in Figure 7, where the flow directions in the flow paths in the pebble bed core at 12.5 h after the loss of flow in PLOFC accident conditions are depicted.

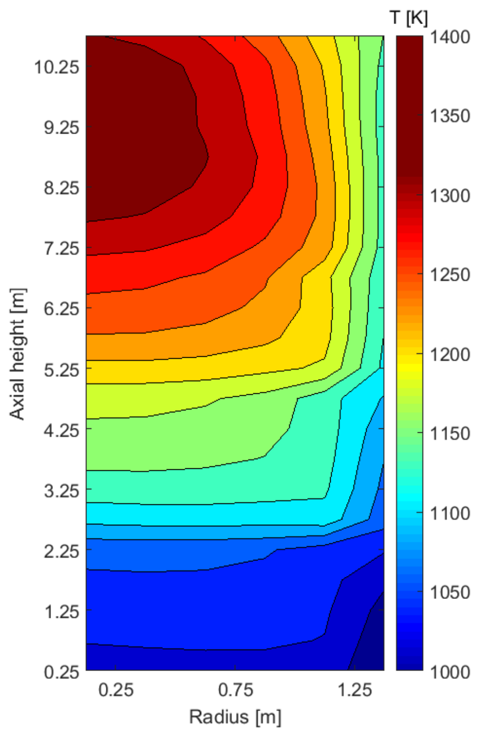


Fig. 6: Average fuel element temperature in the pebble bed core during PLOFC accident, approximately 12.5 h after the start of the accident.

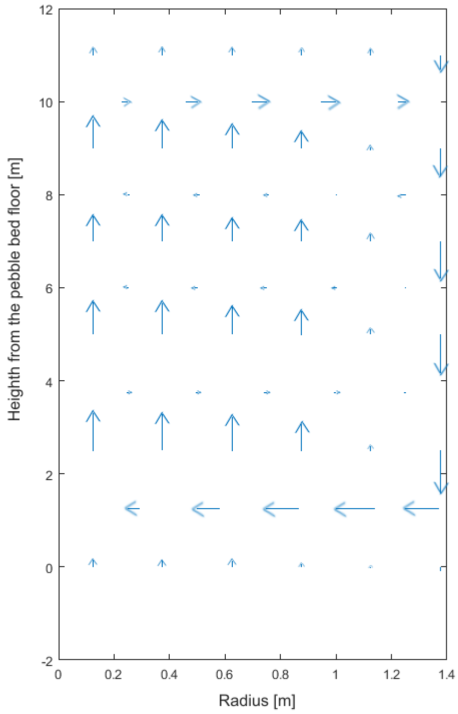


Fig. 7: Flow directions in the pebble bed core flow paths during PLOFC accident, approximately 12.5 h after the start of the accident. The vectors are not in right scale.

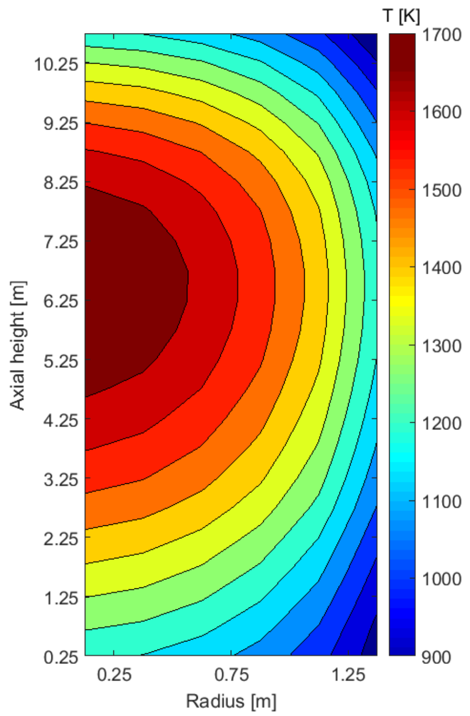


Fig. 8: Average fuel element temperature in the pebble bed core during DLOFC accident, approximately 21.8 h after the start of the accident.

In the DLOFC accident conditions, the maximum fuel temperature (1730 K) was reach at approximately 21.8 hours after the pressure starts to decrease. The temperature profile of the pebble bed during the max fuel temperature (21.8 h) is shown in Fig. 8. Due to the loss of primary system pressure, helium density in the pebble bed is low and the natural convection similar to the PLOFC case is not established. The decay heat is removed from the pebble bed solely by thermal radiation and heat conduction through the pebble bed to the surrounding structures. For this reason, the maximum fuel temperature in the DLOFC is also almost 300 K higher than in the PLOFC accident conditions.

The evolution of maximum fuel temperature in both accident conditions is shown in Fig. 9. These results have been compared to the values extracted from the figures by Zheng et al. [5], also plotted in Fig. 9. The maximum fuel temperature reported in [5] for DLOFC accident is 1492 °C or 1765 K, and for PLOFC accident is 1134 °C or 1407 K. In our MELCOR simulation, maximum fuel temperature is slightly lower (~35 K) in DLOFC accident and slightly higher (~31 K) in PLOFC accident. The timing of the maximum temperature in the DLOFC reported in [5] is approx. 26 h, matching fairly well with the result in this study (21.8 h). In the PLOFC case, Zheng et al. report a time ~7.6 h for the peak value of fuel temperature, which is earlier than what was reported in this study (12.5 h). Also, fast decrease of temperature right after peak value was reached, reported in [5], is missing in the MELCOR result of PLOFC accident.

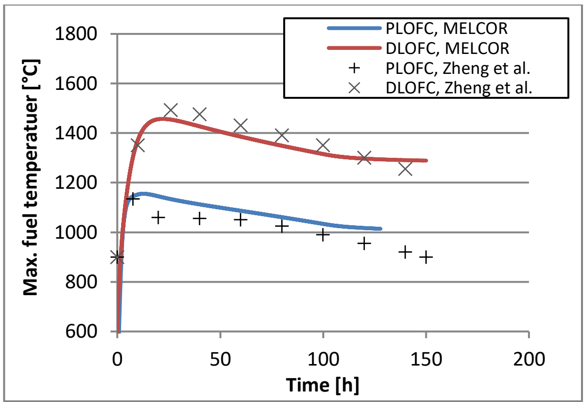


Fig. 9: Comparison of peak fuel temperature evolution in time from the MELCOR simulations to the results by Zheng et al. [5].

The differences between the two analyses can be mainly due to the uncertainties in HTR-PM MELCOR model used in these simulations. The open literature references lack in the description of several geometry detail of the core. These include for example the detailed description of the top and bottom reflectors, where the He is transported through coolant channels from the cold coolant plenum into the pebble bed and from the bottom of the core into the hot coolant plane, respectively. The crude estimation of these structures most likely has an effect on the simulation of the natural convective flow in the PLOFC accident conditions, and can be a cause to the differences in the peak fuel temperature evolution, shown in Fig. 9. Also, the carbon brick insulators were considered as the outmost boundaries the top and bottom boundaries in the MELCOR simulation, whereas Zheng et al. model also the core internals, the RPV and several other structures. In our simulation, adiabatic boundary conditions were set to the top and bottom carbon brick structures, thus adding on to the uncertainties of the model. Additionally, different decay power and reactor power distributions were used in this study, compared to the one by Zheng et al., which can also add to the differences seen in the simulation results.

## II. CONCLUSIONS

In this study, we have used MELCOR 2.2 code to simulate the pressurized and de-pressurized loss of coolant accidents in the HTR-PM. A simplified model input for the HTR-PM was generated based on the open literature description of the pebble bed core and the other reactor structures.

The results of this study showed that during these accident conditions the maximum fuel temperature will remain below 1620 °C, which is a design limitation for the fuel element temperature in LOFC accidents in the HTR-PM [5]. Thermal radiation and heat conduction, and additionally in the case of PLOFC accident conditions the natural convection in the core, are able to remove the heat from the pebble bed to the residual heat removal system, thus limiting the temperature in the DLOFC and PLOFC cases to 1457 °C and 1165 °C, respectively. When compared, the maximum fuel temperature from the MELCOR simulation matched fairly well to the earlier simulation results by Zheng et al. [5], using a different software. The discrepancies in the results are most likely due to the uncertainties in the present MELCOR model of the HTR-PM, relying solely on the open source literature data.

The current version MELCOR 2.2 code also contains models for the fission product (FP) release from the HTGR fuel elements during normal operation of the reactor as well as in the accident conditions. In the future work, an extended study consisting also FP release and transport during LOFC accident conditions using the MELCOR code is envisioned.

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