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PASSIVE SYSTEM ACCIDENT SCENARIO ANALYSIS BY SIMULATION

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ABSTRACT

In this paper, a simulation framework of analysis is presented aiming at evaluating the safety performance of the Residual Heat Removal system (RHRs) of the Chinese High Temperature Gas-Cooled Reactor – Pebble Bed Modular (HTR-PM) under uncertain operation conditions, and components and equipments failures. A transparent and fast model of the passive system has been implemented in MATLAB to reproduce the three-interconnected natural circulation trains of the RHRs, for removing the residual heat of the reactor core after a reactor shut-down. The model is characterized by a one-dimensional mono-phase moving fluid, whose operation is based on thermal-hydraulic (T-H) principles. The model is coded into a Monte Carlo (MC) failure engine for sampling single and multiple components faults at random times and of random magnitudes. Accidental transients of the system are simulated, highlighting equipment contribution to system failure.

Key Words: Passive Safety System, Residual Heat Removal system (RHRs), High Temperature Gas-Cooled Reactor – Pebble Bed Modular (HTR-PM), Scenario Analysis, Monte Carlo Simulation.

1 INTRODUCTION

Generation IV reactor systems (e.g., High Temperature Gas Cooled Reactors (HTGR)) are resorting to the use of passive safety systems, in combination with active safety or operational systems. As passive systems do not need external input, especially energy, to operate [IAEA, 1991], they are expected to contribute significantly to the improvement of plant safety [Mathews et al., 2008]. To achieve this, the design of passive systems must be supported by proper modeling and simulation.

In this paper, we consider the Residual Heat Removal system (RHRs) of the Chinese High Temperature Reactor-Pebble Modular (HTR-PM) [Zhengy et al., 2008]. The function of this system is to remove the residual heat of the reactor core after shut-down. A thermal-hydraulic (T-H) model for scenario analysis has been implemented with characteristics of transparency, for a clear interpretation of the system response, and speed of calculation, to allow for extensive scenario analysis.

Figure 1 sketches the elements of scenario analysis, starting from the collection of system information and the characteristics of the uncertainties affecting the performance of the system function, in terms of plant setting parameters (e.g., power rate), physical condition parameters (e.g., temperatures and pressures), and structural and material properties (e.g., friction and roughness of pipes). Consideration of uncertainties is fundamental for passive safety systems, because the magnitude of the natural forces which drive their operation is small, so that it could be easier for the system behavior to be influenced by the uncertainties, and its robustness poorer than for active system [Marquès et al., 2005; Pagani et al., 2005]. In the end, the design must guarantee that the risk of accidents leading to the dissatisfaction of some of the basic safety functions BSFs (i.e., reactivity control, residual heat removal, primary pressure control and containment release) is not increased.

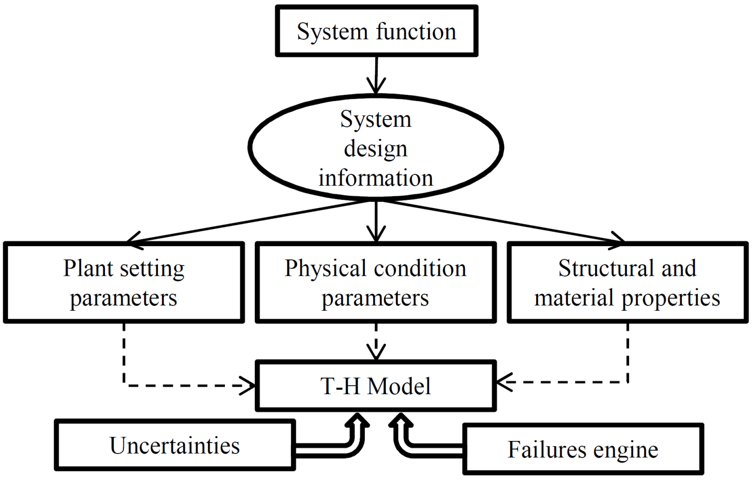

Figure 1 System scenario analysis

The model of the RHRs describes a one-dimensional mono-phase moving fluid, based on thermal-hydraulic (T-H) principles [Zhengy et al., 2008]. A preliminary sensitivity analysis has allowed identifying the most influential parameters affecting the passive system function. These parameters have been the focus of the analysis of the system behavior in major accidents, e.g., pipe blockage, water pipe rupture and RHR trains isolation. The model is embedded in a MC scheme for sampling the uncertain operation condition and single or multiple failures, for an integrated analysis of system response.

The paper organization is as follows. In Section 2, the main system characteristics of the High Temperature Reactor-Pebble Modular (HTR-PM) are briefly introduced. The results of a variance decomposition sensitivity analysis [McKay, 1996] aimed at identifying the most influential parameters for the system function are summarized in Section 3 [Yu et al., 2010a]. Equipment malfunctions and deficiencies are identified by HAZOP [Zio, 2007] in Section 4, and representative accidental scenarios are simulated, as described in Section 5. Finally, some conclusions are drawn in Section 6.

2 THE RESIDUAL HEAT REMOVAL SYSTEM OF THE HTR-PM

High-temperature gas-cooled reactors have developed for nearly 50 years. Today’s Chinese design of the High Temperature Gas-Cooled Reactor-Pebble bed Modular (HTR-PM) is based on the technology and experiences of the HTR-10 10MW high-temperature gas-cooled test reactor (HTR-10) designed in China in 2000.

In Figure 2, a sketch of the HTR-PM layout is shown. At a first glance, the HTR-PM design has the following key technical features [Zhengy et al., 2008]:

- Uranium dioxide (UO_2) fuel kernel coated by tri-isotropic (TRISO) ceramics such as pyrolytic carbon and silicon carbide (SiC), in order to retain fission products in the particle under a fuel cladding temperature of 1600ºC in accident cases.
- A one-zone core design is implemented, consisting of approximately 420,000 spherical fuel elements in a pebble-bed with a diameter of 3m and an average height of 11m, that are charged and discharged in a so-called “multi-pass” mode, which means that before the fuel elements reach the discharge burn-up, they go through the reactor core several times.
- Decay heat in the fuel elements is dissipated by means of heat conduction and radiation to the outside of the reactor pressure vessel, and then taken away to the ultimate heat sink, i.e., the passive RHRs, by water cooling panels on the surface of the primary concrete cell. Therefore, no coolant flow through the reactor core is necessary for decay heat removal in case of loss of coolant flow or loss of pressure accidents.

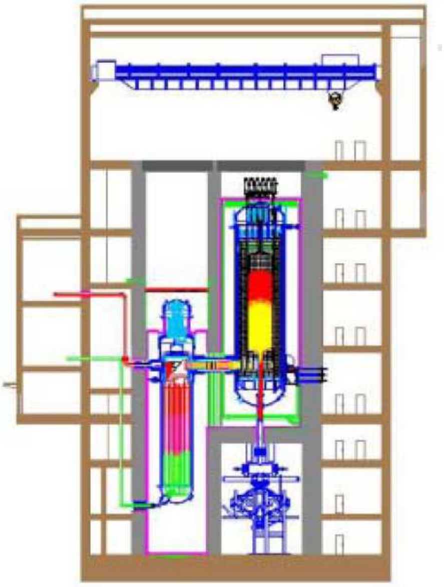

Figure 2 Sketch of HTR-PM

Figure 3 sketches the equipment layout of one of the 3 trains of the RHR system implemented in the HTR-PM: this passive safety system is composed of three circuits dedicated to heat removal, each one being connected to a loop in the primary circuit. The model capability is evaluated according to the maximum outlet of water cooling temperature $T_{w,out}$ reached during the T-H transient; this is the safety parameter with respect to which the success or failure of the system function is defined. In fact, from the engineering experience, when $T_{w,out}$ exceeds the critical temperature $T_c = 126$ [°C] (if $P_w = 0.3$ [bar]), local boiling may occur which can significantly worsen thermal transmission, driving the system into severe damage failure.

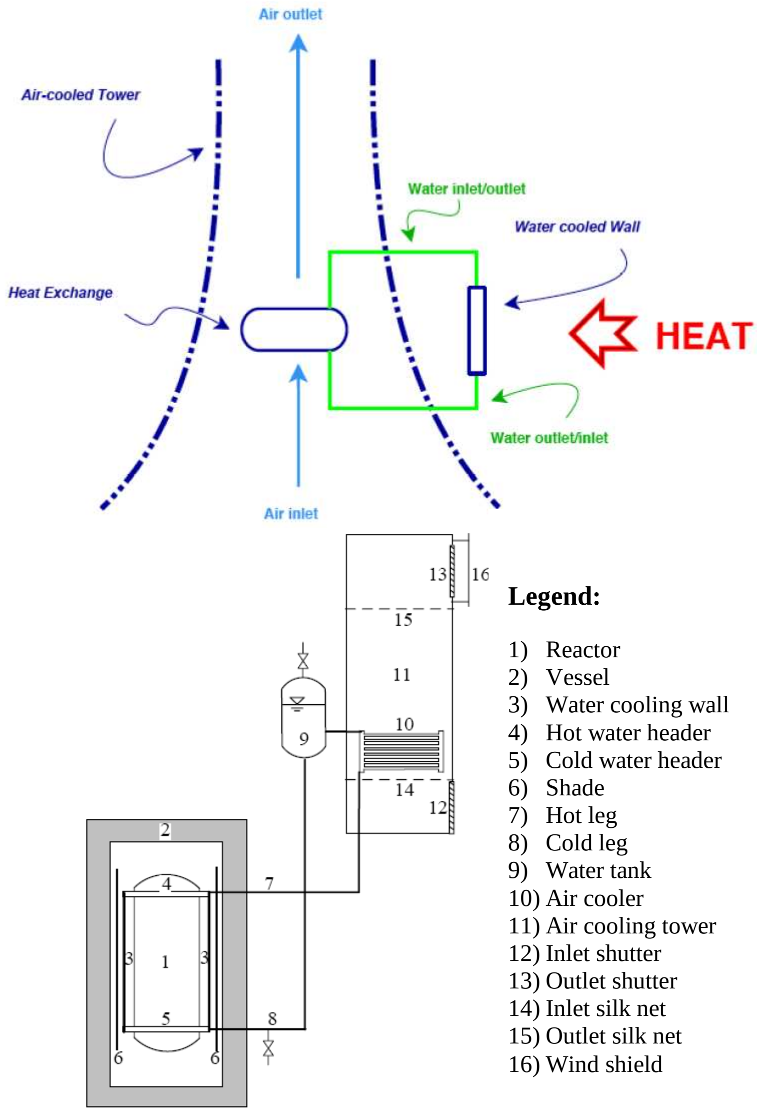

Figure 3 Schematics of 1 train of the RHRs in the HTR-PM [Zhao et al., 2008]

A one-dimensional mono-phase description of the thermo-hydraulic behavior of the RHRs has been implemented in an iterative MATLAB routine and used to simulate normal operation and accidental transients. In negligible computational time (compared to the time constants of system dynamics), the model allows the calculation of $T_{w,out}$.

The T-H code models the following steps of the process:

1. The residual heat radiates from the reactor vessel and other thermal sources to the water in the water-cooling wall;
2. Because of the difference in temperature, natural convection initiates through water, in the water-cooling wall and pipes connected with the air-cooling heat exchanger; then, heat is transferred to the water side of the heat exchanger;
3. The heat is transferred by thermal conduction from the water side to the air side of the heat exchanger, due to the difference of temperature;
4. As the air-cooling heat exchanger is located in the air-cooling tower, natural convection of air sets up and takes heat to the final heat trap–atmosphere.

Table 1 reports the 37 parameters identified as most influential for the system function, by expert judgment. To account for the associated uncertainties, these are described by probability distributions defined on the basis of previous experience and/or information obtained by skilled experts.

N	***Parameter***	***Distribution***	***Note***
1	W	/	Residual heat power
2	$T_{a,in}$	Seasonal/Daily	Temperature of inlet air in the air cooled tower
3	x_{i1}	Uniform	Resistance coefficient of elbow
4	x_{i2}	Uniform	Resistance coefficient of header channel
5	x_{iw}	Uniform	Resistance coefficient of the water tank walls
6	$x_{ia,in}$	Uniform	Sum of the resistance coefficients of inlet shutter and air cooling tower and silk net
7	$x_{ia,out}$	Uniform	Sum of the resistance coefficients of outlet shutter and air cooling tower and silk net
8	$x_{ia,narrow}$	Uniform	Resistance coefficient of the narrowest part of the tower
9	$P_{a,in}$	Seasonal/Daily	Pressure of the inlet air in the cooler tower
10	dx	Uniform	Roughness of pipes
11	H_a	Normal	Height of chimney
12	L_a	Normal	Length of pipes in the exchanger
13	N_a	Normal	Total number of pipes in the air cooler
14	A_f	Normal	Air flow crossing are in the narrowest part of the tower
15	$A_{f,in}$	Normal	Inlet air flow crossing area in the tower
16	$A_{f,out}$	Normal	Outlet air flow crossing area from the tower
17	$A_{f,narrow}$	Normal	Crossing area in the narrowest part of the tower
18	S_1	Normal	Distance between centers of adjacent pipes in horizontal direction
19	S_2	Normal	Distance between centers of adjacent pipes in vertical direction
20	S	Normal	Distance between fins in the ribbed pipe
21	D_a	Normal	Pipes inner diameter in the air cooling exchanger
22	D_o	Normal	Pipes outer diameter
23	D_{outer}	Normal	Rib outer diameter

24	P_w	Normal	Water pressure in the pipes
25	H_w	Normal	Elevatory height of water
26	N_w	Discrete Normal	Number of water cooling pipes for each train
27	L_w	Normal	Length of the water cooling pipes
28	D_w	Normal	Inner diameter of the water cooling pipes
29	D_1	Normal	Inner diameter of the in-core and air cooler connecting pipes
30	D_2	Normal	Inner diameter of the in-core header
31	L_C	Normal	Length of the in-core and air cooler connecting pipes (“cold leg”)
32	L_H	Normal	Length of the in-core and air cooler connecting pipes (“hot leg”)
33	R_i	Log-normal	Thermal resistance of pipes inside of the heat exchanger
34	R_o	Log-normal	Thermal resistance due to the dirt of the pipes fins
35	R_g	Log-normal	Thermal resistance of the gap between fins
36	R_f	Log-normal	Thermal resistance of fins
37	*lamd*	Normal	Heat transfer coefficient of the pipes

Table 1 Parameters relevant for the behavior of the passive RHRs.

Air temperature and pressure variability are inferred by historical data ,collected by a representative Chinese Automatic Weather Station (CAWS) in different months. For example, a typical weather trend for a northern locality of china can be shown in Figures 4 and 5.

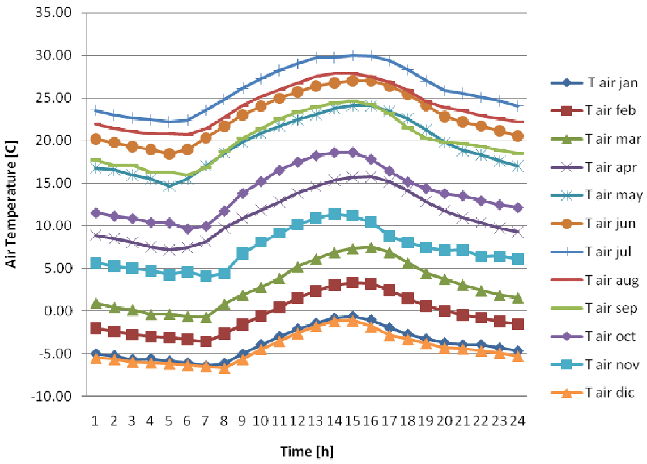

Figure 4 Seasonal variation of the mean air temperature during one day in different months

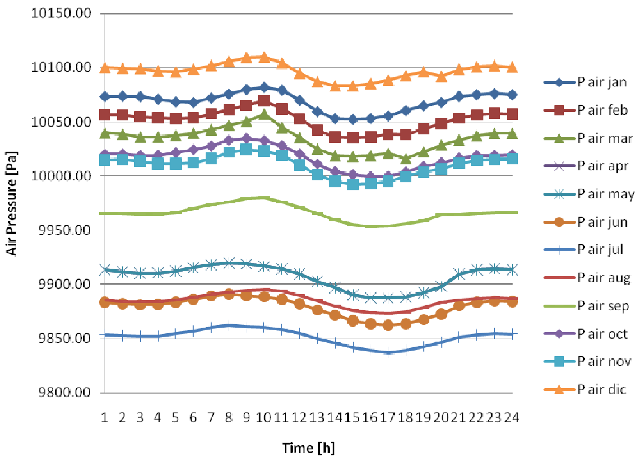

Figure 5 Seasonal variation of the mean air pressure during one day in different months

3 SENSITIVITY ANALYSIS OF THE PASSIVE RHRs MODEL

In a previous work, the variance decomposition sensitivity analysis method has been adopted to assess the impact of uncertainties on the variance of the outlet water temperature $T_{w,out}$ [Yu et al., 2010a]. The results, supported by an application of the Analytical Hierarchical Process [Yu et al., 2010b], reveal that the parameters most influential on the uncertainty of $T_{w,out}$ are the power W , the air inlet temperature of air in the air-cooled tower $T_{a,in}$ and the water pressure in the pipes P_w . This occurs because $T_{a,in}$ and P_w directly influence the air cooling capacity and the critical temperature

T_c, respectively, whereas W is the heat which is absorbed by the system per unit of time: therefore, the smaller is the number of functioning trains, the lower is the overall cooling capacity of the system, the more important is the total heat to be absorbed.

The sensitivity analysis has proceeded to considering the effects of varying simultaneously all plant setting parameters (i.e., power W, the number of pipes in the air cooler N_a, the number of water cooling pipes for each train N_w, etc.), physical condition parameters (i.e., water pressure in the pipes P_w, temperature of air in the air-cooled tower $T_{a,in}$, inlet pressure of the air in the air-cooler tower $P_{a,in}$, etc.), and structural and material properties (i.e., thermal resistance of pipes inside of the heat exchanger R_i, thermal resistance due to the dirty of the pipes fins R_o, etc.). As suspected from the results of the individual inputs, the group of physical configuration parameters is more sensitive than either the group of plant setting parameters or the group of structural and material properties.

Coherently, the following analyses are focused on the inlet air temperature in the air-cooled tower $T_{a,in}$, the water pressure in the pipes P_w and the plant setting parameters such as N_w, N_a and $A_{f,in}$: all these will be sampled for simulating the system response under normal conditions and accidental scenarios.

4 EQUIPMENT FAILURE CHARACTERIZATION

For the analysis of interest, four deviations which may lead to the functional failure of residual heat removal are:

- Higher water temperature in the water cooling wall
- Higher water temperature in the inlet of the air cooler
- Lower air cooling flow in the air cooler
- Lower pressure in the primary cooling pipes

An engineering analysis of these situation lead to the identification of four main types of equipment failures that can run the system into severe situations.

- Reduction of the number of air cooling pipes (N_a), i.e, pipe blockage
- Reduction of the number of water cooling wall pipes (N_w), i.e, water pipe rupture
- The inlet shutters fails partially close, so that $A_{f,in}$ is smaller
- One of the three trains is isolated for some reason, e.g. maintenance

5 SIMULATION OF ACCIDENTAL SCENARIOS

In this Section, the outcomes of the sensitivity and engineering analyses are exploited to define the simulation of a number of accidental scenarios. The calculations have been run with the system at power $W = 1200$ [kW] and water pressure in the pipes $P_w = 0.3$ [bar], under sampled conditions of the variables initial inlet air temperature and initial air pressure in the air-cooled tower, $T_{a,in}$ and $P_{a,in}$, respectively [Yu et al, 2010a; Yu et al., 2010b].

A Monte Carlo (MC) sampling procedure has been developed for injecting equipment faults at random times and of random magnitudes in the RHRs. The set of faults considered are:

- A random number of air pipes in the air cooler (10) for train 1/2/3 fails stuck/broken at time $t_{1/2/3}$ in [1,2880] [min], so that the total number of pipes in each air cooler is equal to $N_a^{1/2/3}$.
- The inlet shutter (12) of the air cooling tower (11) for train 1/2/3 fails stuck at time $t_{4/5/6}$ in [1,2880] [min], providing a corresponding air flow crossing area $A_{f,in}^{1/2/3}$ in each tower.
- A random number of water cooling pipes (3) for train 1/2/3 fails stuck/broken at time $t_{7/8/9}$ in [1,2880] [min], so that the total number of pipes in each air cooler $N_w^{1/2/3}$.
- One of the three trains is unavailable at time t_{10} in [1,2880] [min].

For exemplification, we comment on two of the scenarios simulated. In accidental transient 1, the set of failures in Table 2 have been randomly sampled to occur. The $T_{w,out}$ evolution during the life time of 48 [h] (2880 [min]) is plotted in Figures 6-8 for train 1, 2 and 3, respectively; for comparison, the $T_{w,out}$ evaluated in nominal conditions is also reported (dashed-dotted line).

At time 240 [min], a sudden unavailability of a number of air pipes in the first train causes an increase of the temperature of the coolant in all the trains, that have to endorse the load of more heat removal proportionally to their capabilities: in fact, the temperature of trains 2 and 3 increases much more than for train 1, whose heat capacity has degraded due to the water pipe rupture. At time 1140 [min], the inlet shutter of train 3 fails partially closed: $T_{w,out}$ of trains 1 and 2 increase significantly, whereas the $T_{w,out}$ of train 3 decreases, because of its abrupt decrease in heat capacity, i.e., pipe blockage. Shortly after, at time 1200 [min], train 3 goes out of service. Subsequently, the water temperature in train 3 drops to $T_{a,in}$, reaching the temperature of the cold sink of the air-water exchanger in the air cooler tower, whereas a sharp increase of $T_{w,out}$ is recorded in trains 1 and 2. The maximum value of $T_{w,out}$ is reached in train 2, because all its components and equipments are available along all the system life, so that less resistances are present in this train allowing for a larger heat exchange. In this accidental transient, the system is still able to react to components and equipments failures without exceeding the threshold T_c.

Month		April	
Simulation start time		22.00	
Time of occurrence	**[min]**	**Type of failure**	**Magnitude of failure**
t_1	240	N_a^1	200
t_2	/	N_a^2	/
t_3	/	N_a^3	/
t_4	/	$A_{f,in}^1$	/
t_5	/	$A_{f,in}^2$	/
t_6	1140	$A_{f,in}^3$	8.53
t_7	/	N_w^1	/
t_8	/	N_w^2	/
t_9	/	N_a^3	/
t_{10}	1200	*Failed train*	Yes

Table 2 Failures in the accidental sequence 1

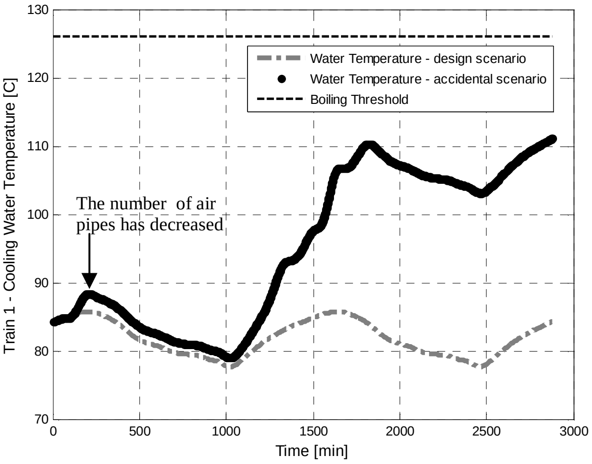

Figure 6 Evolution of the outlet water temperature in RHR train 1.

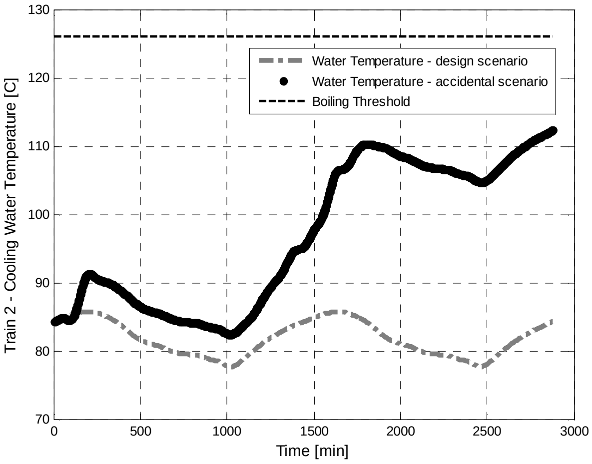

Figure 7 Evolution of the outlet water temperature in RHR train 2.

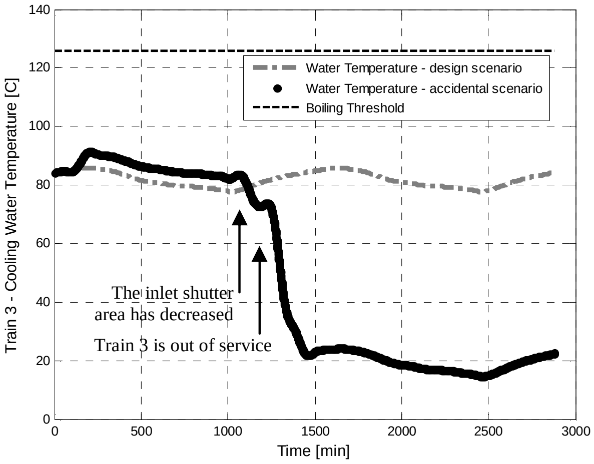

Figure 8 Evolution of the outlet water temperature in RHR train 3.

In accidental scenario 2, $T_{w,out}$ exceeds T_c because the components and equipments states are such to limit the heat transfer capacity, so that the heat decay is larger than the heat releasable to the heat-trap atmosphere. The set of failures characteristic of this scenario are listed in Table 3. The $T_{w,out}$ evolution during the life time of 48 [h] (2880 [min]) is plotted in Figures 9-11 for trains 1, 2 and 3, respectively; for comparison, the $T_{w,out}$ evaluated in nominal conditions is also reported (dashed-dotted line).

Month		April	
Simulation start time		22.00	
Time of occurrence	**[min]**	**Type of failure**	**Magnitude of failure**
t_1	240	N_a^1	100
t_2	1380	N_a^2	200
t_3	/	N_a^3	/
t_4	480	$A_{f,in}^1$	6.0
t_5	960	$A_{f,in}^2$	7.0
t_6	1140	$A_{f,in}^3$	8.0
t_7	970	N_w^1	80
t_8	1260	N_w^2	70
t_9	/	N_a^3	/
t_{10}	1800	*Failed train*	Yes

Table 3 Failures in the accidental sequence 2

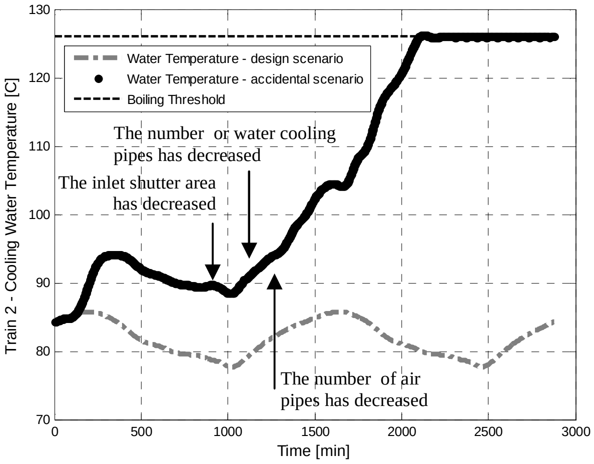

Figure 9 Evolution of the outlet water temperature in RHR train 1.

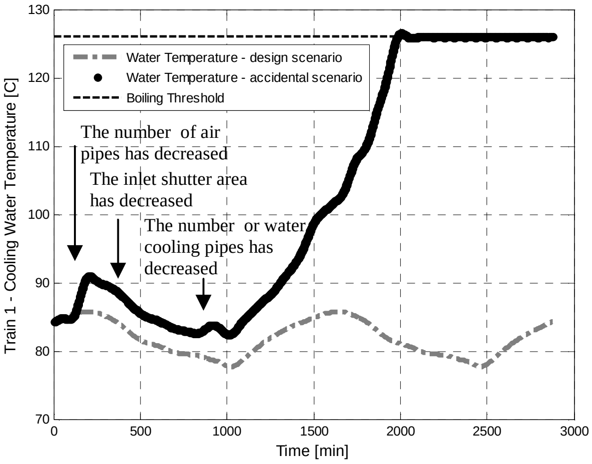

Figure 10 Evolution of the outlet water temperature in RHR train 2.

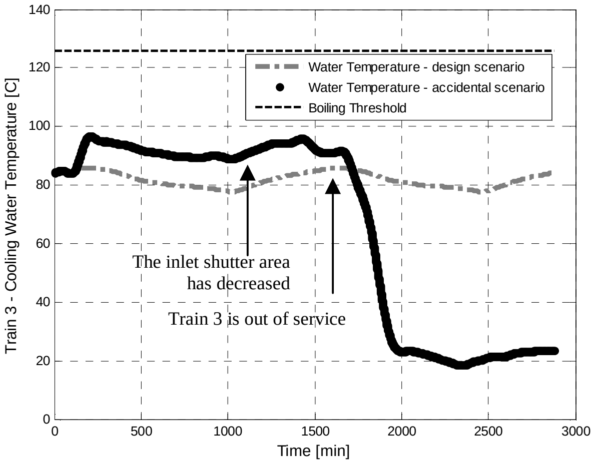

Figure 11 Evolution of the outlet water temperature in RHR train 3.

Like in accident scenario 1, at time 240 [min], a sudden failure of a number of air pipes in the first train causes an increase of the temperature of the coolant in all the trains, that have to remove a greater amount of heat proportionally to their capacities: in fact, the temperature of trains 2 and 3 increases much more than for train 1, whose heat capacity has degraded due to the water pipe rupture. At time 480 [min], the inlet shutter of train 1 fails partially closed: while $T_{w,out}$ of train 1 decreases following the $T_{a,in}$ trend, $T_{w,out}$ reductions in trains 2 and 3 is less significant. The subsequent failure of the inlet shutter of train 2, at time 960 [min] determines a mild increase of $T_{w,out}$. Shortly after, at time 970 [min], the number of water cooling pipes in train 1 decreases, so that a more relevant increase of $T_{w,out}$ is visible. The successive components failures continue degrading the heat transfer capacity of the air cooler, so that the deviation from the temperature nominal behavior (dashed-dotted line in Figures 9-11) increases. The failure of train 3 at time 1800 [min] drives the system into failure, i.e., $T_{w,out}$ exceeds T_c.

6 CONCLUSIONS

In this paper, we have developed a simulation framework for analyzing a three-trains passive Residual Heat Removal system (RHRs) of the Chinese High Temperature Gas-Cooled Reactor – Pebble Bed Modular (HTR-PM). A T-H model is coded into a MC sampling scheme which simulated realizations of both the uncertain operation conditions, and the components and equipments failures. The simulations allow capturing the dependence of the system response on the time and magnitude of components and equipments failures, under uncertain conditions of operation.

Transparency of the model allows understanding of the influence of the uncertainties and of components and equipments failures on the system function. Accuracy and speed of calculation allow the required coverage of scenarios for safety.

ACKOWLEDGEMENTS

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