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METHODOLOGY TO CONSTRUCT BURNUP PROFILE OF FUEL PEBBLES IN PBR

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ABSTRACT

During the normal operation of a pebble bed gas-cooled reactor (PBR), the fuel pebbles undergo a multi-circulation on the basis of online burnup assay. In our last ICONE paper, we proposed a model to describe the relationship between online burnup assay and economy and safety of PBR. It was concluded that improvements on burnup assay accuracy could reduce fuel cost as well as the possibility that excessive burnup of fuel pebble results in unexpected radioactive discharge. However further work was expected on the burnup distribution of pebbles in and out of the core to precisely quantify the relationship. In this paper, the methodology to construct the burnup distribution of fuel pebbles in and out of the core is proposed. Firstly a model for pebble flow circulation is developed to provide a basic simulation framework. Then the irradiation history of fuel pebble could be tracked by combining pebble flow model and burn up calculation. The representative kinematic model and discrete element method (DEM) are introduced to numerically simulate the profiles of pebble flow. The classical batch-tracking methods as well as our newly-introduced DEM-tracking method are presented to perform the time-dependent analysis of pebble burnup. Overall with the burnup data obtained after going through multiple cycles, the burnup distribution of fuel pebbles in and out of the core could be reconstructed through the statistics result according to the pebble circulation model. Finally the quantification of the relationship between the pebble burnup assay and the economy and safety of the PBR would be more precise, thus providing implications on proposing reasonable requirements for accuracy of online burnup assay.

NTRODUCTION

The high temperature gas-cooled nuclear reactor (HTR) is a candidate generation IV reactor being developed as one of the safest, economical and fuel-efficient nuclear powers [1, 2]. In China, researches have been focused on the High Temperature Pebble bed Reactor (PBR) being developed by Tsinghua University [3-5]. The continuous refueling process which requires no shutdown during operation is a major advantage of PBR over other core designs. During the normal operation, the fresh graphite fuel pebbles are introduced from the top and drain slowly in the core, then the burnup of each pebble through exit orifice is online non-destructively

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assessed to determine whether to be recycled to the core or be discharged to a waste storage (Figure 1) . Thus the fuel balls undergo a multi-circulation on the basis of the burnup assay and it is obvious that the accuracy of the online burnup assay is of great importance.

In our last ICONE paper, we proposed a model to describe the relationship between online burnup assay and economy and safety of PBR [6]. On one hand, the burnup assay allow some part of pebbles that are below the burnup limit in the orifice to discharge out of the core. This part of fuel pebbles that are mis-discharged would directly influence the fuel economical efficiency of the core. On the other hand, the burnup assay allow some part of pebbles in the reactor core to exceed the burnup limit no matter what the accuracy is. The part of fuel pebbles will contribute some additional radioactive release during normal operation, which is essentially related with the containing capability of radioactivity in reactor safety. The model is implemented and the influence of measuring accuracy on the reactor safety and fuel cost issues are discussed. It was concluded that improvements on burnup assay accuracy could reduce fuel cost as well as the possibility that excessive burnup of fuel pebble results in unexpected radioactive discharge. However the burnup distribution used in the model is based on some reasonable theoretical hypothesis, so further work was expected on the burnup distribution of pebbles in and out of the core to precisely quantify the relationship.

Due to the varied neutron flux and pebble velocity in the core, the burnup increment of the pebble going through the same number of pass will be different. Therefore after multiple circulations, there are pebbles with different burnup and different histories in the same core position. So the burnup profile of PBR is very complicated taking account of the neutronics and depletion calculation coupled with the pebble flow.

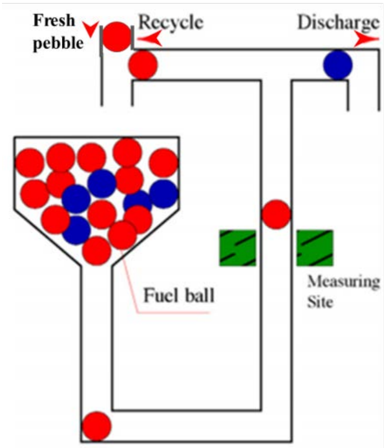

Figure 1. Schematic diagram for fuel circulation [7]

Therefore in this paper, a methodology is proposed to construct the burnup profile of fuel pebbles in PBR. The next section presents the model of pebble flow circulation, which provides a basic simulation framework on how every simulation step connects and cooperates. Section 3 introduces the pebble burnup tracking methods with the combination of the pebble flow model and the burnup calculation. Section 4 illustrates the construction of burnup profile out of the core, which gives the burnup distribution of the discharged and recycled pebbles at the orifice. Section 5 focuses on the construction of burnup distribution in the core. The last section is the general conclusions.

PEBBLE CIRCULATION MODEL

In the realistic PBR operation, after the draining of the first packing of fresh fuel pebbles, it would take a certain number of pebble flow circulations before reaching the stable state for burnup distribution analysis. In order to simulate the pebble flow in PBR realistically, a model for pebble flow circulation is developed (Figure 2).

Pebbles would firstly flow slowly from the top through the core, where the burnup profile could be estimated by the combination of the pebble flow model and the burnup calculation, which will be mainly discussed in the next section. So the irradiation history of fuel pebble will be tracked step-by-step along with its way through the core. Generally the pebble burnup would increase from BU_0 to BU after a pass from top to the bottom, as shown in the Figure 2. So the final burnup of a pebble with multi-pass history could be obtained with the burnup increment through the current pass added by the ending burnup of its last pass.

Then pebbles would drain through exit orifice, where pebbles are online assessed to be recycled to the core or be discharged. The fuel pebble whose measured burnup BU' do not reach the pre-determined threshold will return to the top to pass the reactor core in a random channel/trajectory again. Otherwise the pebble would be marked as discharged and this calculation will be stopped, meanwhile a fresh fuel pebble with zero burnup is introduced at the top for a random new pass. This causation is expressed by the left-side arrow in Figure.2.

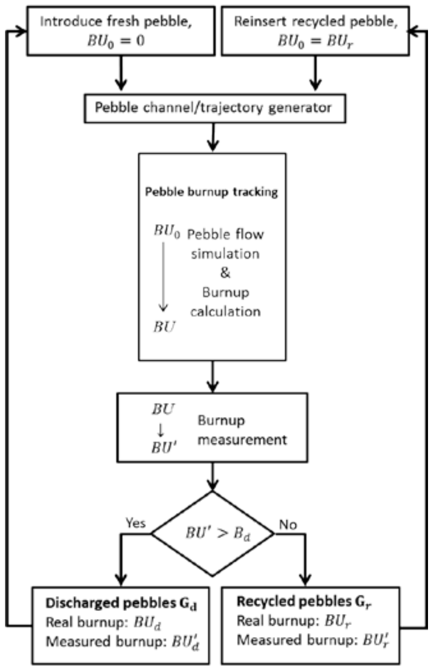

Figure 2. The model of pebble flow circulation in PBR

In a normal burnup calculation, the core is divided into several axial channels, which makes it easier for the pebble history statistics. The pebble channel/trajectory generator in the model randomly chooses different channel or trajectory for a new pass of every pebble flow history. The probability of pebble being assigned to different flow channel has been analyzed previously, by tracing and analyzing the radial positions of massive pebble reinsertion position at the top. So the channel/trajectory the generator decided for a new pass would be given by a random number according to the radial position distribution at the top.

In our last ICONE paper, the function of burnup assay accuracy has been given in the form of a Gaussian function [6], which generates a standard deviation of σ_m when measuring the real burnup μ. Here we introduce a coefficient (1+s) for μ in this equation (Eq.(1)), where the parameter s stands for the systemic error. So both the measuring error σ_m and the systemic error are considered in the function, and this modification would cause an increase/decrease of the original measured burnup.

$$g(\mu, \xi; \sigma_m) = g(\xi - \mu) = \frac{1}{\sqrt{2\pi}\sigma_m(\mu)} e^{\frac{-[\xi-(1+s)\mu]^2}{2\sigma_m^2(\mu)}} \quad (1)$$

Due to the influence of measuring accuracy, the burnup assay simulation in the pebble circulation model would generate a measured burnup BU' which is different from its real burnup value BU. This feature could be implemented by applying this Gaussian function to generate a random number to be the measured burnup BU' around the real pebble burnup BU.

Overall with the burnup data obtained after going through multiple cycles, the burnup distribution of fuel pebbles in and out of the core could be reconstructed through the statistical result according to the pebble circulation model. Besides the influence of burnup assay accuracy as well as the burnup discharging threshold on the burnup distribution could be investigated from the simulation results.

PEBBLE BURNUP TRACKING

In the pebble flow circulation, the irradiation history of fuel pebble could be tracked step-by-step along its way through the core. This could be accomplished by combining the pebble flow model and the burnup calculation.

Pebble flow model

The pebble flow research in the core could be originated from dense slow granular flow study in silos and hoppers. The kinematic model and the discrete element method (DEM) are the representative two methods to numerically simulate the profiles of dense slow pebble flow [8].

Kinematic model

The kinematic model ignores the stress field and attempts a macroscopic continuous diffusion theory of the bulk only with a simplified diffusion equation. Nedderman and Tüzün derived a continuum equation from the constitutive law relating horizontal velocity V_x and horizontal gradient of vertical velocity V_z (Eq. (2)) and the incompressibility condition (Eq. (3)) [9]. Thus a diffusion equation for vertical velocity is obtained as equation (4) for dense slow granular flow in a quasi-two-dimensional silo:

$$V_x = -B\nabla_\perp V_z \quad (2)$$

$$\frac{\partial V_z}{\partial z} + \frac{\partial V_x}{\partial x} = 0 \quad (3)$$

$$\frac{\partial V_z}{\partial z} = B\nabla_\perp^2 V_z \quad (4)$$

where $\nabla_\perp$ is the horizontal gradient, $\nabla_\perp^2$ is the horizontal Laplacian, the kinematic constant B is referred as the "diffusion length", as it has the unit of length. The vertical coordinate z in Eq. (4) acts like "time", when an initial velocity is given at orifice (*z*=0), the vertical velocity "diffuses" upward.

With the boundary conditions of a PBR core geometry, the diffusion equation has been numerically solved in our previous research. The simulated velocity profiles have been compared and validated by the experimental results from reference [10]. Finally the velocity profiles could be applied to pebble burnup calculations, which are the pebble residence time prediction and the channel scheme for PBR geometry.

Discrete element method

The DEM addresses the dynamics of the system at the micro-contact level. In DEM simulations, each particle is accurately modeled as a sphere undergoing realistic frictional interactions with other particles. Generally, DEM starts from treating individual particles (and their physical characteristics) as separate entities in the model and afterwards attempts to give a description of time evolution of the assembly with Newton's equations of motion applied to predict particle trajectories in discrete time steps.

Setting to simulate the granular flow with DEM, a previous work is required that the interparticle forces shall be numerically described since most particles in a granular assembly will form contacts with several other particles. The model is generally stated by a pebble motion which includes the transitional motion of the center of mass and the rotational motion about the center of mass. The basic functions of DEM are as follows [11]: Eqs.(5-7) give descriptions of normal and tangential forces F_n and F_t together with the Coulomb yielding criterion of frictional force. Eqs.(8-9) are functions giving the resultant force and its torch which are based on the Newton's equations of motion.

$$F_{cn} = -k_n \cdot \delta_n + \beta_n \cdot V_n \quad (5)$$

$$F_{ct} = -k_t \cdot \delta_t + \beta_t \cdot V_t \quad (6)$$

$$|F_{ct}|_{max} \leq \mu |F_{cn}| \quad (7)$$

$$m\frac{dv}{dt} = F_c + F_g \quad (8)$$

$$I\frac{dw}{dt} = r \times F_c \quad (9)$$

Where $F_{cn,ct}$ are the normal and tangential contact force, $k_{n,t}$ and $\beta_{n,t}$ are the elastic and damping coefficient, respectively, V is the relative surface velocity components, δ is the deformation. m is mass of element, I is moment of inertia, v is velocity, w is angular velocity, F_c is the resultant contact force, F_g is the gravity of element, r is the distance between interacted elements.

Thus the position, velocity, and angular velocity of each pebble are individually tracked and updated according to the contact models and motion equations, and can be used to reconstruct the flow profiles.

Both of the two methods have been used to simulate the pebble flow profiles in PBR. The kinematic model draws attention for its simplicity and satisfactory results in flow velocity profiles simulation, and it is perhaps the only continuum theory available for the mean flow profile in the core. However it is doubted for its only parameter B, and does not exactly simulate some regions [8]. DEM has been developed as a critical numerical tool to simulate granular dynamics which can construct the complicated microscopic granular mechanism, and it's more realistic-descriptive. Althoough its computational expensive, the large-scale parallel computing technology in the last few years has advanced to allow simulations of continuous pebble flow in a full-sized reactor geometry using DEM method.

Burnup calculation

The fuel pebble burnup is thought to be closely relevant to the nonuniform distribution of neutron flux and the pebble velocity profile. With the pebble velocity profile which could be obtained from both the kinematic model and the DEM method, the time-dependent analysis of burnup can be performed by using the classical batch-tracking method as well as our newly-introduced DEM-tracking method. Both of the two methods are based on employing the burnup calculation program KORIGEN developed by German KfK nuclear research center (Matsson, 1995; Fischer and Wiese, 1983) [12, 13]. The two most important set of parameters for KORIGEN burnup calculation input files are the neutron flux data sequence and the time step sequence. So in the following two methods, KORIGEN is used to compute the radioactivity of the fuel pebble with different burnup under different neutron flux for a given time step sequence.

Batch-tracking method

The core is firstly divided into several axial flow channels. Since the pebbles are not in a flow of uniform speed, we have tried to divide the core into a certain number of channels with unfixed width according to the flow velocity distribution. The channel scheme could be equal-volume or based on residence times of streamlines within each channel.

Secondly each flow channel is divided into several blocks from top to bottom, simulating the pebble movement from one block to next block along the flow channel. The axial blocks could be determined as equal-time or equal-height. According to the channel and block scheme, the average neutron flux and residence time in each block could be obtained with the original given neutron flux distribution and the velocity profiles in the core.

Then the neutron fluxes and residence times of the sequential blocks in each channel could be used as the neutron flux sequence and the time step sequence in KORIGEN calculation, which then calculates the varied burnup in each block in sequence.

Since the pebble passing through one channel in the previous pass has the chance to go through any channel in the next pass, so in a 5–channel core scheme, for example, if an average of 5 times of pebble pass is assumed in a circulation, all possible combination of pebble channel history would be the number of 5^5. Thus after running multiple circulations of pebbles with different channel history, there would be several batches of pebbles in each block, and each batch represents the pebbles in different number of passes through the core. The average burnup and nuclide density of each block would be used to represent the property of all the pebbles in the block.

Then, the pebble discharged from the core bottom with different number of pass and from different channels will be mixed together in the exit orifice. Thus the pebble burnup are tracked, and the burnup distribution of fuel pebbles in and out of the core could be reconstructed through the statistics result of the burnup data.

DEM-tracking

The method of DEM-tracking is proposed to incorporate the burnup calculation into the DEM pebble flow simulation. In this method, DEM would not only give out precise data on pebble positions and time steps, but also trace the pebble burnup of each time step along pebble trajectories.

The DEM method has been implemented by using the large-scale atomic/molecular massively parallel simulator (LAMMPS) developed by Sandia National Labratories (http://lammps.sandia.gov/). The position, time step, angular velocity of each pebble are individually tracked and updated according to the contact model in LAMMPS. The massive amount of precise data can then be used to reconstruct the flow profiles, such as the mean flow, the mean flow velocity, streamlines etc, with some analyzing scripts (codes).

There are two different ways of incorporating the burnup calculation into the LAMMPS running. One is to modify the LAMMPS codes to calculate out the pebble burnup as LAMMPS running out the pebble positions. It would be complicated because of the difficulty in incorporating the KORIGEN source code into the LAMMPS source code. Another is to do post-running analysis. Instead of calculating the burnup in the LAMMPS running, the burnup analysis script has been used to generate burnup given the positions running by the LAMMPS. The burnup analysis script could be a combination of several functions. Firstly the pebble neutron flux data at a certain position along the trajectory could be bilinear-interpolated from the original 2-dimesional neutron flux distribution in the core. Then the time step sequence could be extracted out from LAMMPS output, and it is equally-spaced and could be set manually in LAMMPS. So it is feasible to figure out the neutron flux sequence and the time step sequence for each pebble flow history. As the two most important sets of parameters for KORIGEN burnup calculation are set, the burnup along one single pebble trajectory history could be tracked with the burnup analysis script. Therefore with the LAMMPS running and the post-running burnup calculation, it is not necessary to modify the LAMMPS code to do the DEM burnup tracking. Besides it would be convenient to quickly calculate the burnup tracking without running LAMMPS which would take several hours or days for a full-size simulation.

The batch-tracking burnup calculation could use the simulation results from both the kinematic model and the DEM model, while the DEM-tracking could only be applied with the DEM method since the kinematic model is only available at pebble-contact level.

The batch-tracking method would be less computational expensive, since it easier to deal with the statistical analysis with less pebble channel histories compared to pebble trajectory histories. However the average burnup of each block would be used to represent the property of all the pebbles in the block, so the difference in the burnup of different pebbles in the same block is neglected in the calculation. As for pebbles in the boundary and bottom blocks, where pebble velocities vary a lot, so the mean burnup of these blocks would not be representative enough for the majority of the pebbles in the block. While for the DEM-tracking, a KORIGEN calculation would just stands for a single pebble trajectory history, so it would be more accurate especially for boundary pebbles although it would be more computational expensive.

So in general, the difference of these two burnup calculation methods lies in the way they look at the burnup tracking. The former one is batch-analyzed and would be more time-efficient; the latter one is single-treated and would be more accurate.

BURNUP DISTRIBUTION OUT OF THE CORE

Given the circulation model and the burnup tracking method above, the burnup data collected from the stable circulation could be used to construct the burnup distribution of pebble in and out of the core. In this section the burnup distributions out of the core are discussed.

The burnup data for generating burnup distribution out of the core are mainly collected from the burnup data at the exit orifice. See Figure 2 for the data notification at the bottom exit orifice. After draining out of the core, the real pebble burnup BU is measured to be BU' at the bottom. Then the measured burnup BU' would be compared with the measured burnup threshold B_d. If BU' is higher thanB_d, the pebble would be discharged out and be grouped into G_d. The real burnup and measured burnup of pebbles in G_d would be saved and labeled as BU_d and BU_d' respectively. If BU' is lower than B_d, the pebble would be recycled and be grouped into G_r. The real burnup and measured burnup of pebbles in G_r would be saved and labled as BU_r andBU_r' respectively.

Realistic and measured burnup distribution of pebbles at the orifice

From the pebble circulation model, it is obvious that the realistic burnup distribution of pebbles at the orifice could be obtained by statistically analyzing the real burnup data BU. Meanwhile the measured burnup distribution of pebbles at the orifice could be generated with measured burnup data BU'. The two distributions are expected to be different since our previous simulation has revealed the influence of assay accuracy on measured burnup distribution [6].

Realistic burnup distribution of discharged pebbles

As stated before, the pebbles would be discharged to G_d when they are measured to have a higher burnup than measured burnup threshold B_d. However there are discharged pebbles which do not hit the threshold $B_d$due to assay accuracy, and those are the mis-discharged pebbles. It is directly related with the fuel economomical efficiency. The realistic burnup distribution of pebbles in G_d could be statistically obtained by the real burnup of the discharged pebbles, which has been noted as BU_d. The proportion of the discharged group G_d could be obtained by computing the number proportion of discharged pebbles in the total measured pebble group $(G_d + G_r)$; the proportion of mis-discharged pebbles could be get by calculating the number proportion of the mis-discharged pebbles in G_d.

Realistic burnup distribution of recycled pebbles

The pebbles would be recycled to G_r when they are measured to have a lower burnup than measured burnup threshold B_d. However their realistic burnup could be above $B_d$due to the measurement accuracy, and those are the mis-recycled pebbles. In our previous research, we have assumed a determined risk burnup value B_r, which is higher than measured discharging burnup threshold B_d, for pebbles recycled to the core. Recycled pebbles with burnup beyond B_r at the top of the core have the risk of exceeding the maximum allowable burnup B_m during draining in the core. So special attention should be paid to the risk-recycled proportion in the mis-recycled pebbles. The realistic burnup distribution of pebbles in G_r would be statistically obtained by the real burnup of the recycled pebbles, which has been noted as BU_r.
The proportion of the recycled group G_r could be obtained by computing the number proportion of recycled pebbles in the total measured pebble group $(G_d + G_r)$. The proportion of risk-discharged pebbles could be statistically obtained by computing the number proportion of the risk-discharged pebbles in G_r. It is directly related with the radioactivity safety.

Afterwards, the recycled pebbles would impact the burnup distribution at the top of the core, consequently influencing the general burnup distribution in the core, which is discussed in the next section.

In our last ICONE paper, these burnup distributions out of the core have been generated on some reasonable theoretical hypothesis, and the effects of assay accuracy on the distributions and the different proportions have also been concluded. These conclusions could be validated by comparing the burnup distribution and the proportions under different assay accuracy using the model in this paper.

BURNUP DISTRIBUTION IN THE CORE

From the initial burnup BU_0 at the top to the final burnup BU at the bottom exit orifice, all the tracked pebble burnup during the draining process would be saved and used to construct the burnup distribution in the core. It is mainly contributed by two types of fuel pebbles introduced from the top (see Figure 2). One is the recycled pebbles which have already experienced at least one pass, and the burnup at the top is given by the final burnup at the bottom of its last pass. Another is the fresh pebble which is introduced when a depleted pebble is discharged out.

When constructing the burnup distribution out of core, we could simply analyze the final burnup of each pass without considering the position. While for burnup distribution in the core, the radial and axial position of the pebble should be firstly considered, and then it could be decided that which position the burnup of the current time step should contribute to.

In terms of the two burnup calculation methods mentioned in Section 3, both methods could give the burnup distribution in the core, however the burnup distribution of these two methods would be in different accuracy. For the first batch-tracking method, the burnup data in each block of all possible channel histories would be statistically analyzed to get the average burnup of each block. The burnup distribution in the core in [14] is an example of batch-tracking method although they have used different pebble flow simulation and burnup calculation method. Overall, the batch-tracking method could generate the in-core burn up distribution at the block level. It could give a good overview of the broad burnup distribution, but it is not accurate enough for some specific region such as the boundary. As for the DEM tracking method, it would be more accurate since it tracks the burnup of each pebble instead of taking a group of pebbles as an averaged block. The burnup data of each time step tracked along all the sample pebble trajectory histories would be statistically analyzed to get the mean burnup profiles in the core. As the batch–tracking method has been commonly used before, the following only focuses on the statistical methods of DEM-tracking results to construct the in-core burnup distribution.

Statistical method

Since we have a massive amount of precise data about the positions and the corresponding burnup of the pebbles along the trajectory, it is possible to reconstruct the burnup of the mean flow in the reactor with good accuracy.

By exploiting the axial symmetry of the system, the burnup can be found to be the function of r and z only. The container is divided into bins, and the average burnup is determined within each. The mesh scheme in the core, which defines how the core is divided into bins, is closely relevant to the accuracy of the mean burnup profile. In the z direction, the container is divided into strips 1d across. However, in the r direction the core is not equally divided. Since the number of pebbles between a radius of r and r+Δr is proportional to 2πrΔr, thus the amount of data in bins with high r would be disproportionately large, so dividing the container into bins of a fixed width is unsatisfactory. Therefore a new bin scheme in the radial direction is introduced. The container is divided into regions that are equally spaced in surface area of $1d^2$, where d is the pebble diameter. The number of pebbles in each bin is therefore roughly equal, allowing for accurate averaging in the main cylinder as well as near the boundary. The binning scheme of the core is by reference to [8], which has applied the binning scheme to obtain the mean-velocity profile. This method yields extremely accurate velocity profiles in the cylindrical region. However, it fails to capture crystallization effects in the conical region: since the particles are aligned with the slope of the walls are averaged over a strip in z of width 1d, any effects are smeared out across several bins. So the radial coordinate has been scaled to what it would be if the particle was in the center of the strip. Specifically, if the radius of the container is given by $R(z)$, a particle at (r_n, z_n) is recorded as having radial coordinate $r_n R(z)/R(z_n)$. The modification has no effect in the cylindrical region, while in the conical region, it creates trapezoid-shaped bins which could capture the crystallization effects aligned with the wall.

Thus with the updated mesh scheme, the general statistical method would be concluded as follows. A pebble which has a burnp of BU_n at position x_n at the nth time step makes a burnup contribution of BU_n in the bin which containsx_n. Then each bin would have an accumulated burnup values as well as an accumulated number of the burnup value at the end of the statistical analysis. Lastly the mean burnup of each bin could be obtained by averaging the accumulated burnup values over the accumulated number of burnup values in each bin, finally generating the mean burnup profile in the core.

Burnup profiles in the core

Firstly, the radial and axial burnup distribution could be obtained based on the mean burnup profile in the core, to undertand the varied trend of in-core burnup along the axial and radial direction. Also the 2-dimesional contour plot of the mean burnup profile could be generated, so it would be easier and intuitive to figure out which part of the core has the mean burnup above the maximum allowable burnup B_m. Meanwhile it is possible for us to calculate the number proportion of pebbles in the core with burnup above B_m, so as to obtain the proportion of pebbles which would contribute to the radioactive safety problem in PBR core.

Moreover, intensive analysis could be made in each bin. Since the mean burnup of each bin is determined by collecting and analyzing all the burnup values within the bin, the burnup distribution within each bin could be obtained as well. So it would be possible to know which bin or part of the core geometry has the highest probability of exceeding the maximum allowable burnup B_m. It is expected that the burnup distribution of bins in the center would be more concentrated than bins in the boundary region. So the risk probability of boundary bins would be higher than that in the center region because of the disperse distribution over the high burnup range due to the slow boundary layer. This could also be helpful to adjust the bin scheme if the burnup distribution of some region is tested to be unsatisfactory.

In general, all of the analyses of the burnup profiles in the core could provide implications for controlling the radioactivity release and improve the reactor safety in the PBR core.

CONCLUSIONS

In this paper, the methodology to construct the burnup distribution of fuel pebbles in and out of the core is proposed to further precisely quantify the relationship between online burnup assay and economy and safety of PBR.

In order to simulate the pebble flow in PBR realistically, a model for pebble flow circulation is developed in the Section 2. It provides a basic simulation framework on how every simulation step connects and cooperates. In the pebble flow circulation, the irradiation history of fuel pebble could be tracked step-by-step along its way through the core. So Section 3 introduces the pebble burnup tracking methods with the combination of the pebble flow model and the burnup calculation. The representative two pebble flow models, the kinematic model and the discrete element method (DEM), are introduced to numerically simulate the profiles of dense slow pebble flow. Then the classical batch-tracking method as well as our newly-introduced DEM-tracking method are presented to perform the time-dependent analysis of pebble burnup. Section 4 illustrates the construction of burnup profile out of the core, which gives the realistic and measured burnup distribution of pebbles and the burnup distribution of the discharged and recycled pebbles at the orifice. Section 5 discusses the construction of burnup distribution in the core, which mainly focuses on the statistical method of DEM-tracking results.

Overall with the burnup data obtained after going through multiple cycles, the burnup distribution of fuel pebbles in and out of the core could be reconstructed through the statistics result according to the pebble circulation model. Moreover, the influence of burnup assay accuracy as well as the burnup discharging threshold on the distribution could be checked or adjusted from the simulation results. All of this could provide implications on proposing reasonable requirements for accuracy of online burnup assay.

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