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A PROPOSED MODEL TO DESCRIBE THE RELATIONSHIP BETWEEN ONLINE BURNUP ASSAY AND ECONOMY AND SAFETY OF PEBBLE BED REACTOR

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ABSTRACT

Online burnup measurement is a unique feature for pebble bed gas-cooled reactor and the fuel balls undergo a multi-circulation on the basis of the online burnup assay. It is ascertained that the accuracy of the online burnup assay is related with the economy and safety of pebble bed reactor. In the economical perspective, the burnup assay accuracy allow some part of pebbles that are below the burnup limit in the orifice to be discharged out of the core. In the safety view, the burnup assay allow some part of pebbles in the reactor core to exceed the burnup limit. In this paper, a mathematical model is proposed to establish the relationship. The model is implemented based on some reasonable theoretical hypothesis, and the influence of assay accuracy on the reactor safety and fuel cost issues are discussed based on the simulated results given by different assay accuracy. It is ascertained that improvements on burnup assay accuracy could save the fuel cost and improve the PBR economical efficiency as well as reduce the probability of radioactive release due to over-irradiation and enhance the safe reliability of PBR. Further research on the burnup distribution of pebbles in and out of the core and the burnup assay model are expected to provide some implications on proposing reasonable requirements for accuracy of online burnup assay.

INTRODUCTION

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, a large interest has been initiated on pebble bed HTR (PBR) and researches have been focused on the High Temperature Reactor-Pebblebed Modules (HTR-PM) being developed by Tsinghua University [3-5]. The notably introduced fuel pebble in PBR consists of uranium-based fuel

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core mixed with phenolic resin and a coat of graphite. 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 assessed to determine whether to be recycled to the core or be discharged to a waste storage (Fig. 1) [6-8]. Thus the fuel balls undergo a multi-circulation on the basis of the burnup assay and it is obvious that the precision and accuracy of the online burnup assay is of great importance.

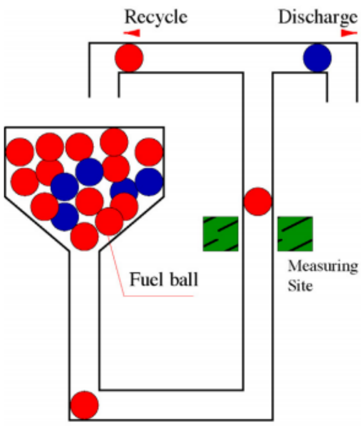

Figure 1. Schematic diagram for fuel circulation [6].

The main idea of this paper is firstly based on investigating the requirements on burnup assay accuracy. It can be also understood as to find how accurate is accurate enough for burnup assay. The answer to this question could be relevant to two possible aspects in terms of the fuel economical efficiency and reactor safety.

On one hand, assay accuracy is associated with fuel economical efficiency, because 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. The fuel cost could be markedly lowered down with better burnup accuracy in HTR-PM, which has an average flow rate of six thousand pebbles/day [6]. In the meantime the number threshold for the mis-discharged fuel pebbles sets the requirement for the assay accuracy. 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 with burnup value beyond the limit will contribute some additional radioactive release during normal operation, which is essentially related with the containing capability of radioactivity in reactor safety. Meanwhile one could propose a sound requirement for accuracy of online burnup assay with a given threshold for this additional radioactive release. Therefore, the accuracy of burnup assay has a great impact on the fuel economical efficiency and the reactor safety, and in turn the requirements on burnup assay accuracy could be proposed considering the radioactive release safety limit and fuel cost efficiency.

In the paper, a mathematical model is proposed to reveal the influence of the assay accuracy on the fuel economical efficiency as well as the reactor safety. In the next section, the theories and model are proposed to establish the relationship between burnup assay accuracy and the fuel economical efficiency and the reactor safety. In section 3, the model is implemented on some reasonable theoretical assumptions, and the influence of measuring accuracy on the fuel economy and safety issues are discussed based on the simulated results. The last section is the general conclusions and discussions.

THEORIES & MODEL

In this section, theories and model on the measured burnup distribution of pebbles at the orifice, discharged and recycled pebbles are proposed sequentially to establish the relationship between burnup assay accuracy and the fuel economical efficiency and the reactor safety.

Measured burnup distribution of pebble at the exit orifice

$$P(\xi, H_b) = \int_0^{+\infty} f(\mu, H_b) g(\mu, \xi; \sigma_m) d\mu \quad (1)$$

Equation (1) gives measured burnup distribution of pebble at the exit orifice, where μ is the burnup, and H_b is the discharging position in the core. $f(\mu, H_b)$ is the realistic probability density distribution of pebble burnup (regarded as realistic burnup distribution) at the exit orifice, and $g(\mu, \xi; \sigma_m)$ is the function of burnup assay, and it is simplified as a Gaussian function. The measured burnup distribution of pebbles at the exit orifice can be derived by the convolution of the realistic burnup distribution of pebbles at the exit orifice and the function of burnup assay (Eq. (1)). If the ideal realistic burnup distribution could be assumed as a uniform distribution (see red solid line in Fig. 2), the function of burnup assay would generate a standard deviation of σ_m when measuring a burnup of μ (the dashed line), consequently their convolution would result in a uniform distribution with rising edge and tail.

The proportion of discharged and mis-discharged pebbles

$$P_d = \int_{B_d}^{+\infty} P(\xi, H_b) d\xi = \int_{B_d}^{+\infty} d\xi \int_0^{+\infty} f(\mu, H_b) g(\mu, \xi; \sigma_m) d\mu \quad (2)$$

Equation (2) gives the proportion of discharged pebbles at the exit orifice with measured burnup beyond B_d, where B_d is the discharge burnup level. This discharged proportion, P_d, can be obtained by computing the integral of $P(\xi, H_b)$ over $[B_d, +\infty]$.

When the double integral order of Eq. (2) is changed, the inner integration is the realistic burnup distribution of discharged pebbles $P_d(\mu, H_b)$ (Eq. (3)), so the proportion of discharged pebbles P_d can also be obtained by the integration of $P_d(\mu, H_b)$ on $[0, +\infty]$ (Eq. (4)). Moreover, its integration on $[0,\ B_d]$, $P_{d<B_d}$(Eq. (5)), is the proportion of pebbles that are below the measured threshold B_d but are measured to discharge out of the core, which can be regarded as mis-discharged proportion in the discharging pebbles.

$$P_d(\mu, H_b) = \int_{B_d}^{+\infty} f(\mu, H_b) g(\mu, \xi; \sigma_m) d\xi \tag{3}$$

$$P_d = \int_0^{+\infty} P_d(\mu, H_b) d\mu \tag{4}$$

$$P_{d<B_d} = \int_0^{B_d} P_d(\mu, H_b) d\mu \tag{5}$$

It can be notified that the P_d which is the proportion of pebbles that are measured to exit the fuel recycling are contributed by two groups of pebbles. Most are attributed to pebbles that really reached the discharging threshold, others are the mis-discharged pebbles that do not hit the threshold due to the accuracy of burnup measurement. The latter part $P_{d<B_d}$ is directly related with the fuel economomical efficiency and the fuel cost could be greatly reduced with lower $P_{d<B_d}$. Thus the relationship between the burnup assay accuracy and the fuel economical efficiency in PBR operation has been clarified through above theories.

The proportion of recycled and risk-recycled pebbles

$$P_r = \int_0^{B_d} P(\xi, H_b) d\xi = \int_0^{B_d} d\xi \int_0^{+\infty} f(\mu, H_b) g(\mu, \xi; \sigma_m) d\mu \tag{6}$$

Equation (6) gives the proportion of recycled pebbles at the exit orifice with measured burnup below B_d. This recycled proportion, P_r, can be obtained by the integration of $P(\xi, H_b)$ over $[0, B_d]$. When the double integral order of Eq. (6) is changed, the inner integration $P_r(\mu, H_t)$ (Eq. (7)) is the realistic burnup distribution of recycled pebbles, where H_t is the refueling position in the core. The proportion of recycled pebbles P_r can also be derived by the integration of $P_r(\mu, H_t)$ on $[0, +\infty]$ (Eq. (8)). Certainly, it can be noticed that the recycled proportion P_r are contributed mostly by pebbles with burnup that are really below the discharging threshold B_d, and a small amount are attributed to the mis-recycled pebbles that are beyond the threshold due to the accuracy of burnup measurement. We assume 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 risk-recycled proportion $P_{r>B_r}$ can be obtained by the integration of $P_r(\mu, H_t)$ on $[B_r, +\infty]$ (Eq. (9)), giving the risk-recycled part in the recycling pebbles.

$$P_r(\mu, H_t) = \int_0^{B_d} f(\mu, H_b) g(\mu, \xi; \sigma_m) d\xi \tag{7}$$

$$P_r = \int_0^{+\infty} P_r(\mu, H_t) d\mu \tag{8}$$

$$P_{r>B_r} = \int_{B_r}^{+\infty} P_r(\mu, H_t) d\mu \tag{9}$$

$$P_{\mu>B_m} = \int_{B_m}^{+\infty} d\mu \int_{H_t}^{H_b} P(\mu, \nu)\, d\nu \tag{10}$$

Overall, the recycled pebbles would impact the burnup distribution at the top of the core, consequently influencing the general burnup distribution in the core. Equation (10) gives the proportion of pebbles with burnup exceeding the maximum allowable burnup B_m in the core, where ν is the position coordinates. This part is directly related with the containing capability of radioactivity in core safety. Thus the relationship between the burnup assay accuracy and the safety of reactor has been illustrated through above functions.

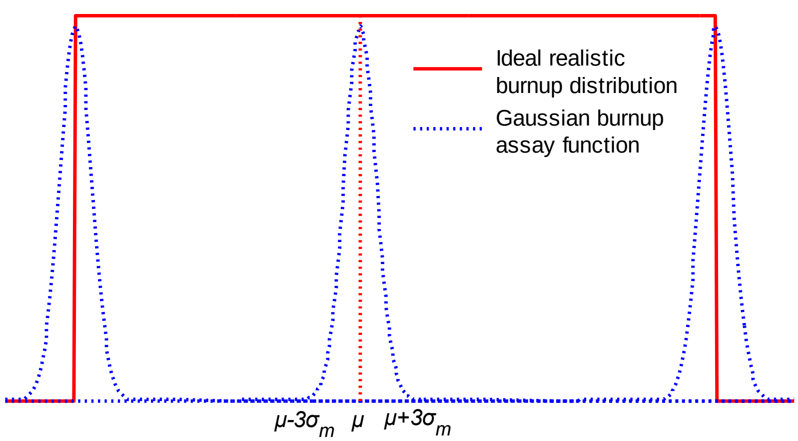

Figure 2. The schematic illustration diagram of Eq. (1).

ASSUMPTIONS & IMPLEMENTATIONS

Assumptions

To generate the quantified results of the above theories and functions, assumptions are firstly made on two basic distribution functions, the realistic burnup distribution at the exit orifice and the function of burnup assay.

The realistic burnup distribution at the orifice

$$f(\mu, H_b) = \int_{u_{min}}^{u_{max}} \frac{1}{\sqrt{2\pi}\sigma_o} e^{\frac{-(x-u)^2}{2\sigma_o^2}} du \qquad (11)$$

Due to the varied pebble trajectories and neutron flux distribution, pebbles of the same cycle have different burnup increase after going through the core, generating a burnup distribution at the bottom exit orifice. We introduce a reasonable assumption of Gaussian burnup distribution at the orifice, as given by the integrand of Eq. (11), where u is the average burnup at the orifice of the cycle, σ_o is the standard deviation of the realistic burnup distribution. There are pebbles that have gone through different cycles at the orifice during the normal operation of PBR, so the general burnup distribution at the orifice is reasonably derived by the integration of the Gaussian distribution of different cycles, with the average burnup u varied between u_{min} and u_{max}. Therefore the expected realistic burnup distribution at the orifice could be anticipated as a uniform distribution over $[u_{min}, u_{max}]$.

The function of burnup assay accuracy

$$g(\mu, \xi; \sigma_m) = g(\xi - \mu) = \frac{1}{\sqrt{2\pi}\sigma_m(\mu)} e^{\frac{-(\xi-\mu)^2}{2\sigma_m^2(\mu)}} \qquad (12)$$

The exact expression of $g(\mu, \xi; \sigma_m)$ is given as Eq. (12) in the form of Gaussian function, which generates a standard deviation of σ_m when measuring the real burnup μ. Since it is verified in measurements [6, 9, 10] that the measured relative standard deviation (relative STD) σ_m/μ would decrease with burnup μ, so we may assume here a parabolic relation, $\frac{\sigma_m}{\mu} = a\mu^2 + b\mu + c\ (a > 0)$. Thus the measured absolute standard deviation (absolute STD) is given as Eq. (13).

$$\sigma_m = a\mu^3 + b\mu^2 + c\mu \quad (a > 0) \qquad (13)$$

Simulation and implementation

The parameters used in the subsequent simulations are reasonably based on the expected operation of HTR-PM. It is assumed the average burnup u to vary within (9,100) GWd/tU; the measured burnup threshold B_d=90 GWd/tU; risk burnup value B_r=96 GWd/tU. The STD of realistic burnup distribution at the orifice is assumed as σ_o=3 GWd/tU, whereas it is actually thought to be the function of the burnup since the deviation of real burnup distribution would increase as pebbles passing through more cycles in the operation. On the basis of our measurement results that the relative accuracy could be better than 5% at the discharging burnup threshold [6, 8], three assumed relative measured STD functions of $\sigma_{m1}, \sigma_{m2}, \sigma_{m3}$ are given in Fig. 3, indicating the decrease of burnup assay accuracy. Then the theories and model in section 2 are implemented with MATLAB coding to generate quantified results for implications on reactor economy and safety.

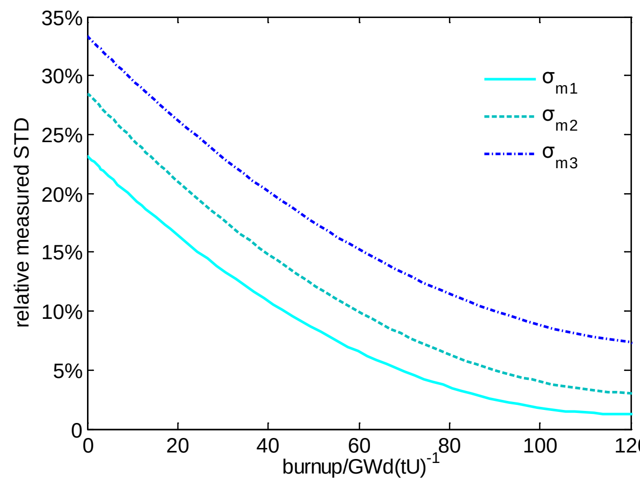

Figure 3. Three assumed relative measured STD functions of $\sigma_{m1}, \sigma_{m2}, \sigma_{m3}$.

Normalized realistic and measured burnup distribution of pebbles at the orifice

With the assumed parameters above, the Eq. (11) is implemented and the normalized realistic burnup distribution of pebble at the orifice $f(\mu, H_b)$ is given by the red solid line in Fig. 4. It is generally a symmetric uniform distribution with rising edge and tails in the Gauss error function form given the reasonable theoretical hypothesis, whereas the burnup distribution is actually more of asymmetry considering that σ_o would increase with the burnup as mentioned above. Figure 4 also gives the influence of assay accuracy on measured burnup distribution. It shows that most impacts of the measured accuracy are exerted on the higher burnup region, referring to the extended and deformed trailing end of the measured curve compared to the original real burnup distribution. With the fixed σ_o, the influence of different accuracy on measured burnup distribution can also be seen in Fig. 4. The measured burnup distribution would be extended more to the high burnup region with a decreased burnup assay accuracy, comparing the more streching curve of σ_{m3} to that of σ_{m1}.

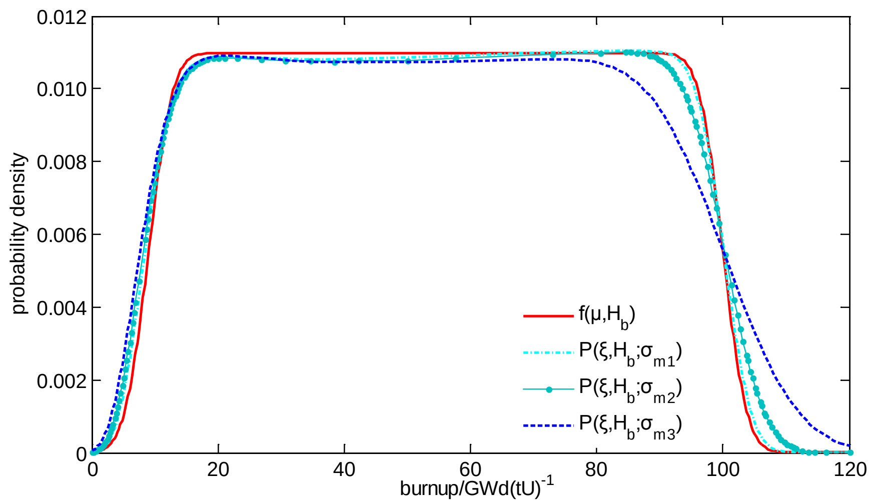

Figure 4. Normalized measured burnup distribution $P(\xi, H_b)$ at the orifice compared with the realistic burnup distribution $f(\mu, H_b)$.

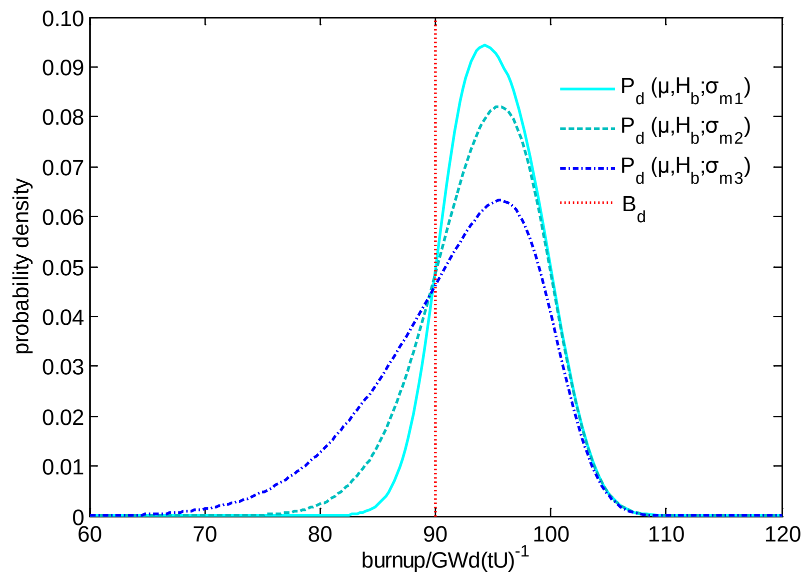

Figure 5. Normalized realistic burnup distribution of discharged pebbles $P_d(\mu, H_b)$ given by $\sigma_{m1,}\, \sigma_{m2}, \sigma_{m3}$.

The proportion of discharged and mis-discharged pebbles

The implementation of Eq. (3) gives the realistic burnup distribution of discharged pebbles. Figure 5 shows the normalized results derived by different σ_m. The area below the curve is the proportion of discharged pebbles P_d, within which the part on the left side of threshold is $P_{d<B_d}$, the mis-discharged proportion in the discharging pebbles. The value of P_d and $P_{d<B_d}$ derived with different $\sigma_{m1,}\, \sigma_{m2}, \sigma_{m3}$ are given in Table 1.

Figure 5 shows that the discharged proportion is mostly attributed to the pebbles with burnup above the threshold. It also reveals the influence of assay accuracy on burnup distribution of discharged pebbles. The curve is extended more on both sides with increased measured STD σ_m, and the area below the curve increases slightly with a decreased assay accuracy (also see the P_d value in Table 1), indicating that the discharged proportion might increase with a poor measurement accuracy. In HTR-PM, 6000 pebbles are averagely measured at the orifice per day and about 400 pebbles are discharged out of the core, generating an approximate discharge portion of 1/15, however the P_d derived in this section is around 11%. The deviation between the realistic and simulated results could be due to the assumptions on the evaluation of σ_o and σ_m. Moreover, it is apparent in Fig. 5 that the left part of the discharged area (the left side of threshold) increases with increased measured STD σ_m (also see the $P_{d<B_d}$ value in Table 1), showing that

mis-discharged proportion would increase with poor accuracy. Therefore a little advance on burnup assay accuracy could save the fuel cost and improve the PBR economical efficiency.

Table 1. The proportion of discharged pebbles P_d and the mis-discharged proportion in P_d derived by $\sigma_{m1,} \sigma_{m2}, \sigma_{m3}$.

	P_d	$P_{d<B_d}$
σ_{m1}	11.13%	9.55%
σ_{m2}	11.31%	18.77%
σ_{m3}	11.87%	33.86%

The proportion of recycled and risk-recycled pebbles

The implementation of Eq. (7) gives the realistic burnup distribution of recycled pebbles. Figure 6 shows the normalized distribution derived by different σ_m. The area below the curve is the proportion of recycled pebbles P_r, within which the part on the right side of risk threshold B_r is $P_{r>B_r}$, the risk-recycled proportion that are above the burnup risk threshold but are measured to be recycled due to the assay accuracy. The value of P_r and $P_{r>B_r}$ derived with different $\sigma_{m1,} \sigma_{m2}, \sigma_{m3}$ are given in Table 2.

It can be seen from Fig. 6 that the recycled proportion is mostly attributed to the pebbles with burnup below the threshold, and the influence of assay accuracy on burnup distribution of recycled pebbles is also shown in Fig. 6. The trailing end of the curve is more extended with increased measured STD σ_m and the area below the curve decreases slightly with a decreased assay accuracy. This is also shown by the P_r in Table 2 and indicates that the recycled portion P_r would decrease with a lower measurement accuracy.

Table 2. The proportion of recycled pebbles P_r and risk-recycled proportion in P_r derived by $\sigma_{m1,} \sigma_{m2}, \sigma_{m3}$.

	P_{r}	$P_{r>B_r}$
σ_{m1}	88.87%	0.00%
σ_{m2}	88.70%	0.13%
σ_{m3}	88.13%	0.83%

Moreover, the right part of the recycled area (the right side of risk threshold) increases with incremental measured STD σ_m, as shown in Fig. 6 (also see $P_{d<B_d}$ in Table 1). Thus the risk-recycled proportion would increase with lower assay accuracy. Although there are deviations between the realistic recycled pebble and the simulated results due to the assumptions, it is ascertained that improvements on burnup assay accuracy could reduce the probability of radioactive release due to over-irradiation and enhance the safe reliability of PBR.

Whereas the proportion of pebbles in the core with burnup beyond the maximum allowable burnup, $P_{\mu>B_m}$, can not be simulated and implemened at the present, since the general burnup distribution in the core is still under investigation.

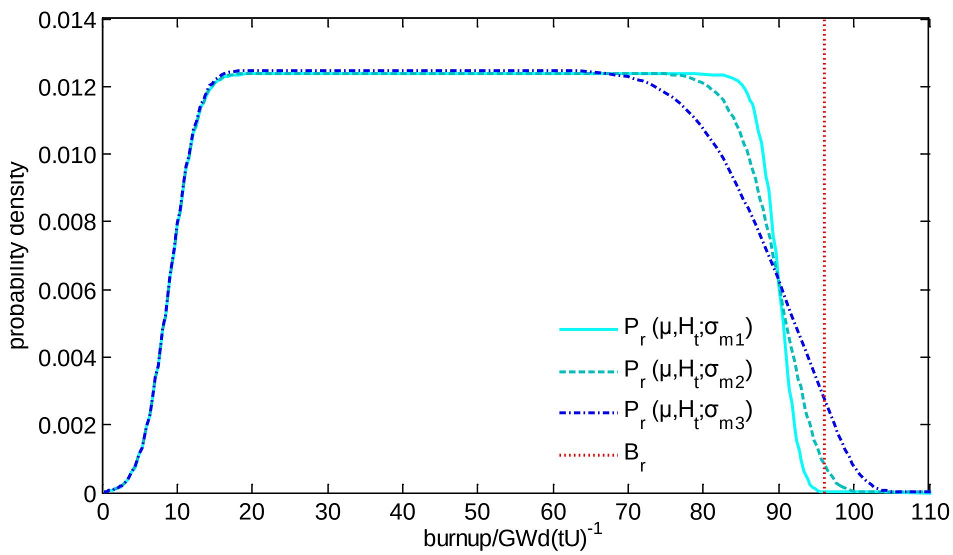

Figure 6. Normalized realistic burnup distribution of recycled pebbles $P_r(\mu, H_t)$ given by $\sigma_{m1,} \sigma_{m2}, \sigma_{m3}$.

CONCLUSIONS & DISCUSSION

In the paper, the mathematical model is proposed to reveal the influence of the assay accuracy on the reactor safety as well as fuel economical efficiency. The theories and models are firstly proposed to establish the relationship between assay accuracy and the reactor safety and fuel economical efficiency. The measured burnup distribution and four kinds of pebble proportion are mainly concerned in terms of the fuel economical efficiency and reactor safety in this paper. The proportion of discharged pebbles at the exit orifice with measured burnup beyond B_d , the proportion of mis-discharged pebbles with burnup that are below the measured threshold B_d but are measured to discharge out of the core, the proportion of recycled pebbles at the exit orifice with measured burnup below B_d, and the proportion of risk-recycled pebbles with burnup beyond B_r but are measured to recycle to the core. Then the model is implemented based on some reasonable theoretical hypothesis, and the influence of measuring accuracy on the reactor safety and fuel cost issues are discussed based on the simulated results given by different assay accuracy. It is shown that the measured burnup distribution would be extended more to the high burnup region with decreased burnup assay accuracy. As a consequence, the discharged proportion might increase with poor measurement accuracy and the mis-discharged proportion would also increase with poor accuracy. Meanwhile the recycled portion P_r would decrease with lower measurement accuracy and the risk-recycled proportion would increase with lower accuracy. Therefore it is ascertained that improvements on burnup assay accuracy could save the fuel cost and improve the PBR economical efficiency as well as reduce the probability of radioactive release due to over-irradiation and enhance the safe reliability of PBR.

It is generated in the paper that there are deviations between the simulated results and the expected discharging in HTR-PM. This could be attributed to the two basic theoretical hypotheses proposed in the paper. Firstly, the realistic burnup distribution of pebble at the orifice is obtained with ideal assumptions as a symmetric uniform distribution with rising edge and tails in the Gauss error function form. Additionally the STD σ_o would be the function of the burnup since it would increase as pebbles passing through more cycles in the operation. Thus actually the realistic burnup distribution at the orifice is more of asymmetry and even not in the forms of tailed uniform distribution. Therefore further investigations on the simulation of real burnup calculation and burnup distribution at the orifice are necessary to verify and modify the assumptions. Secondly, the impact of burnup assay accuracy on the measured burnup distribution is simplified as a Gaussian function with a STD of σ_m, which is assumed as a cubic function of burnup. However the coefficients of the cubic function and even the exact realistic function form are still uncertain, and more accurate burnup assay experiments is under plan. Additionally, other parameters, i.e. the u_{max} for the average burnup at the orifice, and the risk threshold B_r for pebbles in the core, are supposed to be justified according to the expected operation of HTR-PM. Lastly as for the safety issue, only the proportion of risk-recycled pebbles are estimated in the paper, whereas the proportion of pebbles with burnup beyond the maximum allowable burnup in the core requires further research on the in-core burnup calculation and distribution.

Therefore, generally two aspects of work should be concerned to precisely quantify the relationship between the pebble burnup assay and the economy efficiency and safety of the PBR operation. One is the simulated realistic burnup distribution of pebbles in and discharged out of the core. It is ascertained that the bunup distribution is closely related with the pebble flow and neutron flux distribution [11, 12], thus future combination of the pebble flow model and the burnup calculation is planned, and we have already made some attempts [13, 14]. The other is the burnup assay model establishing the relationship between the burnup and burnup assay accuracy, and further experiments on optimizing the burnup assay accuracy is required. We have already investigated on the burnup assay prototype with experiments and simulations with on burnup assay prototype and analyses on the gamma spectra of Cs-137 [6, 10], which is the usual burnup indicators in PBR pebbles. It is expected that with the two aspects of future research, the basic theories and model proposed in this paper could provide some implications on proposing reasonable requirements for accuracy of online burnup assay.

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