Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Nuclear Engineering and Design 236 (2006) 669–676
Nuclear Engineering and Design
www.elsevier.com/locate/nucengdes

Investigation of bounds on particle packing in pebble-bed high temperature reactors

Abderrafi M. Ougouag [a,*], Jan Leen Kloosterman [b,*], Wilfred F.G. van Rooijen [b], Hans D. Gougar [a], William K. Terry [a]

[a] Idaho National Laboratory, P.O. Box 1625, Idaho Falls, ID 83415-3885, USA
[b] Delft University of Technology, Faculty of Applied Sciences, Physics of Nuclear Reactors, Mekelweg 15, 2629 JB Delft, The Netherlands

Received 6 October 2004; received in revised form 18 December 2005; accepted 19 December 2005

Abstract

Models and methods are presented for determining practical limits of the packing density of TRISO particles in fuel pebbles for a pebble-bed reactor (PBR). These models are devised for designing and interpreting fuel testing experiments. Two processes for particle failure are accounted for: failure of touching particles at the pressing stage in the pebble manufacturing process and failure due to inner pressure buildup during irradiation. The second process gains importance with increasing fuel temperature, which limits the particle packing density and the corresponding fuel enrichment. Suggestions for improvements to the models are presented.

1. Introduction

The packing fraction of fuel particles within a pebble is an important factor in predicting the performance of the fuel during normal operation. Determining which packing fraction and which particle size would result in the best performance is an interesting and, so far, unsolved, problem. Yet, it must be tackled before an optimal design can be devised and before a rational testing program can be planned for the fuel from that optimal design. This paper is a first attempt at determining the influence of the packing fraction on the impact of failures of TRISO particles in the 2.5-cm radius fuel zone of a pebble with overall diameter of 6 cm.

The upper limit for the packing of TRISO particles in a fuel pebble is dictated by the particle failure rate and the effect of the packing on that failure rate. The performance (i.e., failure or retention of integrity) of fuel particles depends on many factors. The first is the proximity of particles within the pebble. This is because particles that are too close to one another could be damaged during the isostatic pressing stage of the pebble manufacturing process. The second is the burnup level expected to be achieved by the fuel within the particle. This factor correlates to the pressure exerted on the silicon carbide (SiC) shell by gaseous fission products and CO. This factor also correlates with the irradiation damage that invariably accumulates in the SiC layer and with the irradiation-induced shrinkage of the pyrolytic carbon (PyC) layers. See for an extensive descriptions of these effects references Nabielek et al. (2004), Wang et al. (2004), Petti et al. (2004) and Martin (2001). Because of weakening of the SiC (i.e., lowering of its mechanical strength) when subjected to fast neutron irradiation at temperatures above 1000 °C, this factor (i.e., the effect of burnup) is sensitive to the fuel temperature history during irradiation. All these artifacts contribute to the failure of the particle. The burnup also correlates to the radiological hazard, which in turn enters the definition of the impact of particle failure. The models developed in this work incorporate all of these considerations.

In the next section, a proper qualification for the impact of fuel particle failures is discussed and a quantitative measure for it, the "effective impact" of failure, is defined. In Section 3, the models and programs used to calculate the failure rate from proximity are discussed. Section 4 describes a model that relates the packing fraction to the fuel enrichment needed in order to preserve the reactivity of the fuel. Subsequently, the fuel enrichment is related to the final discharge burnup, from which the expected failure rate due to burnup can be derived.

* Corresponding authors.
E-mail addresses: Abderrafi.Ougouag@inl.gov (A.M. Ougouag), J.L.Kloosterman@tudelft.nl (J.L. Kloosterman).

0029-5493/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.nucengdes.2005.12.006

Section 5 presents a discussion of the results, while the final section iterates its principal conclusions and points to upcoming further development.

2. Effective impact of fuel particle failure

Fuel particle failures are undesirable because of the potential radiological hazard to personnel. In addition to their potential safety impact, failures are indications of possible weakening of the TRISO particles and could, therefore, result in limitations on the operability of the reactor. In all cases, an objective measure of the magnitude of the problem that fuel failures would cause can be correlated to the radiological hazard of the materials they normally contain and retain. Therefore, the "effective impact" of fuel particle failures can always be quantified in terms that incorporate or correlate to that radiological hazard. In this study, a simple approach is taken that considers as the effective impact merely the amount of releasable volatile nuclides contained in the particles that fail. This quantity can easily be related to release into the atmosphere and health impact on personnel or the public, inasmuch as models for said release, subsequent transport and potential health effects are assumed to exist. Such models exist but are beyond the scope of the present study.

By modeling the impact as merely the amount of volatile nuclides present within failed particles, the implicit assumptions are that the nuclides are released congruently from within the failed particles and travel to the off gas and beyond to the receptors (facility workers or general public) equally congruently. It is also implicitly assumed that their relative toxicity levels (expressed in terms of such commonly accepted indices as the derived air concentrations) are essentially equal. That is, the current model ignores the difference of toxicity between the various volatile radioactive nuclides present within the fuel particles. Both of these assumptions of congruent release and migration, and of equal toxicity, should be relaxed in a more comprehensive definitive model. Finally, another assumption is implicit in the models of this paper. It is assumed that the volatile nuclides build up linearly as a function of the burnup level. This assumption should also be relaxed in a comprehensive model as some volatile nuclides may have reached their equilibrium concentration during irradiation.

As described later, the fuel fraction variation in a pebble is counterbalanced in our models by a commensurate variation of the fuel enrichment in such a way that the initial reactivity of the fuel is preserved. From this, it follows that the "effective impact" of particle failures is proportional only to the number of failures, the volume of the fuel kernel in a single particle, and the expected burnup. The latter is approximated by a linear function of the initial fuel enrichment (see Section 4.2—a more complete future model should relax this assumption). Once the number of particles per pebble and the fuel enrichment are fixed, the only remaining factor to be determined is the failure fraction for the given pebble design. This number depends on the failure mechanisms being considered, of which two are considered in this paper: failure by particle proximity (or manufacturing effects) and failure by burnup (or radiation damage and pressure effects). These mechanisms are considered next, in order.

3. Particles proximity factor in fuel particles failure

The existence of damage to fuel particles caused by pair-wise proximity of said particles is a well established experimental fact. The predictive determination of the fraction of particles that fails via this mechanism requires the definition or identification of a critical distance between particles below which the particles are assumed to fail. To be more general, the number of particles that fail is assumed to be a specific fraction of all the particles that are closer to their nearest neighbor than this critical distance. Assuming that this critical distance is known, the number of particles that are within that distance from their nearest neighbor must be determined. In the early times of TRISO particle manufacturing, the failure fraction for this mechanism could be as high as 6×10^{-5}, but relatively recent over-coating techniques have reduced this fraction to 1.4×10^{-5}, which is considered to be the lower limit for the cold pressing technology. In accordance with ref. Nabielek et al. (2004), the failure fraction in our models is set to 1.4×10^{-5}.

3.1. Spatial distribution law for independently and randomly distributed particles

If the fuel particles are very small and dilute, it can be assumed that they are randomly and independently distributed within the fueled zone of the pebble. In particular, it can be assumed that (a) the chance of a fuel particle being located in any particular portion of the fueled zone is the same for all particles, (b) the fact that a fuel particle is present in a particular zone does not affect the chance that other particles be present in the same zone, (c) the chance of a particle being present in a region of the fueled zone is the same for regions of equal volume and (d) the total number of fuel particles and the total number of sub-regions within the fueled zone are large. These assumptions (a–d) are well approximated if the particles are very small and the packing fraction is low. When these assumptions are met, the distribution of particles is given by Poisson's law (Evans, 1955). If μ is the average particle density, the average number of particle present in volume V becomes $m = \mu V$, and the probability of finding exactly n particles in the region within a distance r from some arbitrary point is

$$p_n(r) = \frac{((4/3)\pi r^3 \mu)^n}{n!} \exp\left(-\frac{4}{3}\pi \mu r^3\right). \tag{1}$$

This probability distribution applies only if the conditions for validity of a Poisson distribution are applicable. In reality, the Poisson distribution may not be applicable. The latter situation is discussed in Section 3.3.

3.2. Distribution of pair-wise inter-particle distances for Poisson-distributed particles

When particles are spatially distributed according to the equations of the previous section, the distances between the particles are distributed according to a law that can be obtained analytically. This is done next.

Without loss of generality, assume a particle is located at the origin of a coordinate system, i.e. at $r = 0$. The probability that no other particle is present between that location ($r = 0$) and some specific value of r is $p_0(r)$, given by

$$p_0(r) = \frac{((4/3)\pi r^3 \mu)^0}{0!} \exp\left(-\frac{4}{3}\pi\mu r^3\right) = \exp\left(-\frac{4}{3}\pi\mu r^3\right). \quad (2)$$

The probability that the next particle is in the shell between r and $r + \mathrm{d}r$ is given by $p_1(\mathrm{d}r)$, that is

$$p_1(\mathrm{d}r) = \frac{(4\pi r^2 \mu \mathrm{d}r)^1}{1!} \exp\left(-\frac{4}{3}\pi\mu r^2\, \mathrm{d}r\right). \quad (3)$$

When the exponential is expanded in a Taylor series of its argument and only terms of order 1 in dr are retained, this latter equation reduces to $p_1(\mathrm{d}r) = 4\pi r^2 \mu\, \mathrm{d}r$. Combining the probability of not having any particle between 0 and r and that of finding exactly one particle in the shell between r and $r + \mathrm{d}r$, one obtains the probability that the distance between the particle at $r = 0$ and its next nearest neighbor is between r and $r + \mathrm{d}r$. That probability is given by

$$f(r)\mathrm{d}r = 4\pi r^2 \mu \exp\left(-\frac{4}{3}\pi\mu r^3\right) \mathrm{d}r. \quad (4)$$

From this equation, the fraction of all particles that are within some specified distance of their next nearest neighbor can be calculated by integrating the equation between 0 (corresponding to "point" particles) and that distance, say r_c. The expression for that fraction f_d is

$$f_d = 1 - \exp\left(-\frac{4}{3}\pi\mu r_c^3\right). \quad (5)$$

Clearly, the distribution given by Eq. (4) and the resulting proximity fraction of Eq. (5) fail to apply when either or both of the particle size and the packing fraction become large and the Poisson distribution is no longer valid. In those more realistic situations, the distribution of pair-wise distances between particles must be obtained differently. This is discussed in the next section.

3.3. Realistic distribution of finite-sized particles

The situations best described by Eq. (1) and the equations derived from them are those in which the postulates for a Poisson distribution, as enumerated above, apply. Such situations are approximated when the particle radius and the particle packing fraction are both very small. In reality, departures from those conditions and postulates will arise if the packing fraction is large enough for the particles not to be appropriately considered as dilute. They arise also from the finite nature of the particles (i.e., they are not points but do have a finite non-negligible radius) and from the dependence in their relative positions. The latter situation arises merely from the fact that two particles cannot overlap, and therefore their respective locations are not independent. The absence of independence is more marked the higher the packing fraction. For such real situations, the Poisson distribution is not applicable, and a different distribution function must be used. Analytical distribution functions that better represent the real situation have been developed and can be found in the literature. However, in this paper a numerical approximation for the particle distribution is obtained. Concomitantly, the distribution of pair-wise particle distances is computed using a program written specifically for this purpose.

A program was written to estimate the number of particles that will "touch" each other in a realistic pebble design with a fuel zone diameter of 5 cm. The practical definition of "touching" each other is necessarily not absolute, as mathematically touching means having exactly one point in common. In correspondence with ref. Nabielek et al. (2004), two particles are considered as touching if the distance between their centers coordinates falls below a cut-off distance of 180 μm.

The touching evaluation program operates by first randomly positioning particles in the fuel zone of a pebble. Then it calculates the distance between a particle and its nearest neighbor. The latter process is repeated for all fuel particles in the pebble and a histogram-like distribution is derived with an interval width of 5 μm. Results of this program and a comparison with the Poisson distribution are given in Fig. 1. As can be seen, only for tiny particles, with radii of about 0.01 cm, does the Poisson distribution reasonably describe the distance between nearest neighbors. For standard fuel particles with a radius of 0.05 cm, the Poisson distribution deviates considerably from the actual one. From the peak at 0.1 cm in the lower plot of Fig. 1, one can deduce that at high densities many particles are positioned very close to each other.

Despite the large differences between the two distributions, the Poisson distribution may be used if the predefined cut-off distance below which particles are deemed touching each other is chosen sufficiently large. The use of the Poisson distribution is acceptable in this situation because the cumulative fraction for it and that derived from the computationally obtained distribution converge (i.e., coincide) for a sufficiently large cut-off distance. In Fig. 2, it is shown that at a cut-off distance of 180 μm, the difference between the two cumulative fractions is negligible for 35,000 particles per pebble, and is only 25% for 15,000 particles per pebble (about 0.55 for the actual distribution and 0.80 for the Poisson distribution). Because the model with a cut-off distance of 180 μm and a fail fraction of 1.4×10^{-5} predicts reasonably well the number of particle defects in German-made fuel pebbles (Nabielek et al., 2004), and other sources are lacking, we use these same data. From Fig. 2, it can be estimated that the difference between the Poisson distribution and the actual one (taken here as the computationally modeled distribution) will be limited to a factor of 2 for a particle density of 5000 per pebble and up.

4. Fuel enrichment as a function of the particle packing

When the number of fuel particles per pebble is modified, other parameters have to be changed accordingly to preserve criticality of the reactor. Among others, these can be the total fuel inventory in the core (number of fuel pebbles) or the fuel enrichment. Because it is easily recognized that it is more

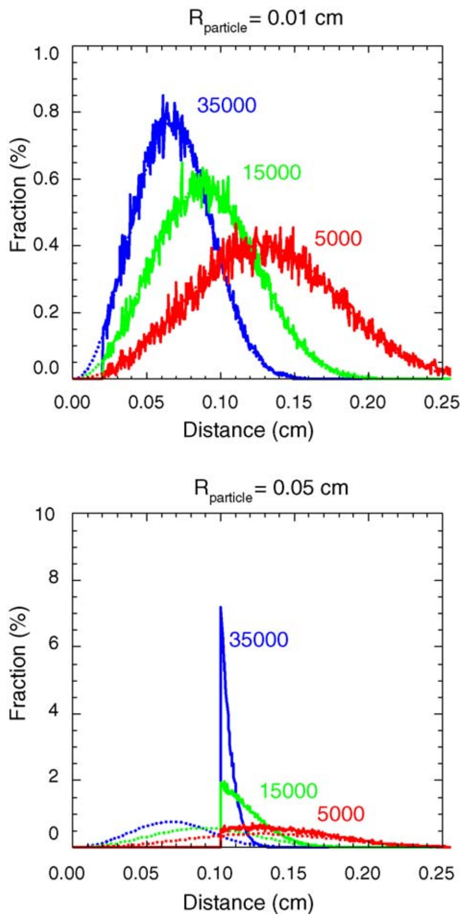

Fig. 1. Distribution of the distance between immediate neighbor particles for two particle sizes (artificially small particles with radius of 0.01 cm, and standard fuel particles with radius of 0.05 cm) with the number of particles per pebble as a parameter. In each plot, the highest peak corresponds to the largest number of particles. Only for tiny particles can the distribution be described well with the Poisson distribution (dotted lines).

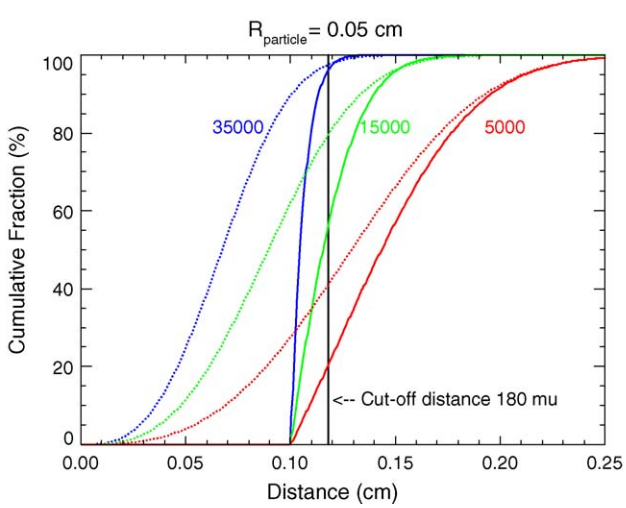

Fig. 2. Cumulative distribution of the distance between immediate neighbor particles with the number of particles per pebble as a parameter. The dotted lines represent the Poisson distributions according to Eq. (5); the solid lines are the actual distributions.

practical to determine the optimum fuel design for a specified reactor size rather than to optimize the overall design by altering the reactor size or configuration, the latter parameter (fuel enrichment) has been selected for use in this study. In this section, an analytical model is derived that relates the fuel enrichment to the fuel loading per pebble in such a way that the initial infinite multiplication factor of the fuel, k_∞, is preserved.

4.1. k_∞ as a function of enrichment and fuel loading

The infinite multiplication factor of a specified fuel composition and configuration is given by the well-known four factor formula $k_\infty = \varepsilon p f \eta$, where ε is the fast fission factor, p the resonance escape probability, f the thermal utilization and η is the number of fission neutrons per absorption in the fuel. The fast fission factor can be assumed to be independent of the fuel enrichment and will be arbitrarily set to unity. The thermal utilization f writes (Duderstadt and Hamilton, 1976; Zweifel, 1973):

$$f = \frac{\Sigma_a^F}{\Sigma_a^F + \Sigma_a^F(\Phi_M/\Phi_F)(V_M/V_F)}. \tag{6}$$

Both in the numerator and the denominator, the thermal-averaged cross sections should be used. Assuming the same energy dependence for both the absorption cross section of the fuel and the moderator, the cross section values at energy of 0.025 eV can be used. For graphite as the moderator, this value equals 32E−5 cm^{-1} (Duderstadt and Hamilton, 1976). The absorption cross section of the fuel depends on the atomic fuel enrichment $e = N_5/(N_5 + N_8)$ according to $\Sigma_a^F = [e\sigma_a^5 + (1-e)\sigma_a^8](N_5 + N_8)$ where the symbols have their usual meanings and where 5 stands for U-235 and 8 stands for U-238. For the microscopic cross sections of the fuel nuclides, the thermal values should be used ($\sigma_a^5 = 678b$; $\sigma_a^8 = 2.73b$ (Duderstadt and Hamilton, 1976)). The flux disadvantage factor, which is the ratio of the neutron flux in the moderator zone and the fuel zone (Φ_M/Φ_F), is unity within 1% for an HTR because of the small size of the fuel particles. Only the ratio of the moderator volume and the fuel volume (V_M/V_F) depends significantly on the particle packing fraction in the fuel pebble.

The number of fission neutrons per absorption in the fuel depends on the atomic fuel enrichment according to

$$\eta = \frac{\nu e \sigma_f^5}{e\sigma_a^5 + (1-e)\sigma_a^8}, \tag{7}$$

with $\sigma_f^5 = 577b$ (Duderstadt and Hamilton, 1976) and with an average number of neutrons per fission $\nu = 243$.

The resonance escape probability p writes:

$$p = \exp\left[\frac{-N_F V_F}{\xi \Sigma_s^M V_M} I_{\text{eff}}\right]. \tag{8}$$

Here, $\xi = 0.158$ (Duderstadt and Hamilton, 1976) is the average logarithmic energy decrement per collision, $\Sigma_s^M = 0.4\,\text{cm}^{-1}$ is the scattering cross section of the moderator in the resonance region and I_{eff} is the effective energy shielded resonance integral. Within the narrow resonance approximation (which has to be relaxed in an improved future model), the latter can be split into a "volume" term and a "surface" term, $I_{\text{eff}} = I_{\text{NR}}^{\text{V}} + I_{\text{NR}}^{\text{S}}(P_0)$, so named because it is only the second term that depends on the first-flight escape probability P_0 (Zweifel, 1973). To account for the fact that resonance neutrons escaping from a fuel kernel can reach another kernel without any interaction in between, the Dancoff-corrected first-flight escape probability, P_0^*, should be used instead of P_0. To derive the functional dependence of the resonance integral on the number of fuel particles in the pebble, three approximations are made. First, the Wigner rational approximation (Duderstadt and Hamilton, 1976; Zweifel, 1973; Bell and Glasstone, 1970) is used for the first-flight escape probability, P_0, as given by

$$P_0 = \frac{1}{1 + \langle R \rangle \, \Sigma_t^{\text{F}}}. \tag{9}$$

Here $\langle R \rangle$ is the mean chord length of the fuel particle (Bell and Glasstone, 1970; de Kruijf and Kloosterman, 2003). Second, to obtain P_0^* from the expression for P_0, the Dancoff-corrected mean chord length $\langle R \rangle/(1-C)$ is applied into Eq. (9) instead of $\langle R \rangle$. Here, C is the Dancoff factor of the fuel, which can be calculated analytically for pebble-bed reactors (Bende et al., 1999). Third, a series expansion is derived for P_0^* and the higher order terms ($C^2 P_0^2$ and up) are neglected. Following these three steps, the Dancoff-corrected first-flight escape probability is shown to be given by

$$P_0^* = \frac{(1-C)P_0}{1-CP_0} \approx (1-C)P_0(1 + CP_0 - \ldots)$$
$$\approx P_0 - C(P_0 - P_0^2) = P_0 - C \, \langle R \rangle \, \Sigma_t^{\text{F}} P_0^2. \tag{10}$$

If the first-flight escape probability of a particle does not change with varying enrichment, which is a reasonable assumption if the size of the fuel kernels remains constant and the enrichment does not significantly alter the macroscopic total cross section of the fuel, the effective resonance integral can just be written as a linearly decreasing function of the Dancoff factor: $I_{\text{eff}} = I_1 - CI_2$. To check the validity of this assumed behavior of the resonance integral as a function of the Dancoff factor, eigenvalue (k_∞) calculations were performed on a fuel particle surrounded with an amount of graphite that results in a system equivalent to one with packing values of 6009, 9542, 13,128, 16,489 or 20,054 particles per pebble, but with no allowance for the reflector graphite. Calculations were carried out with the SCALE code system (SCALE-5, 2005) at a temperature of 800 °C. The Dancoff factors for these cases were calculated using the analytical procedure described in ref. Bende et al. (1999). From the k_∞ values found for these cases, and the values of ε, f and η computed according to Eqs. (6) and (7), the value of the resonance escape probability for each case can be derived, from which the resonance integral can be calculated. Fig. 3 shows the resulting resonance integral as a function of the Dancoff factor C. Clearly, the behavior can be considered as linear to first approximation with the coefficients shown in the figure.

From the formulas and data above, the fuel enrichment can be calculated as a function of the number of fuel particles per pebble with the constraint that the k_∞ of the fuel remain constant. For the pebble-bed VHTR in development at the INL, the Next Generation Nuclear Plant (NGNP), with a fuel enrichment of 8.1% and 13,200 particles per pebble (MacDonald et al., 2003), the k_∞ of the fuel was found to be 1.499 (derived from a k_∞ calculation with the SCALE code system (SCALE-5, 2005)). This is the target value for all other fuels considered in this section. Fig. 4 shows the resulting fuel enrichment as a function of the number of particles per pebble.

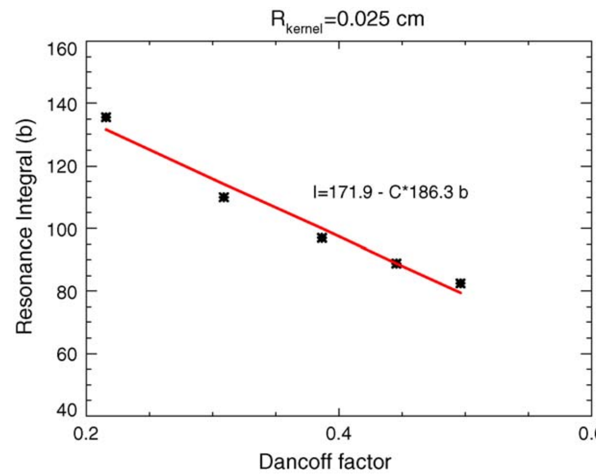

Fig. 3. The resonance integral as a function of the Dancoff factor for fuel kernels with a radius of 0.025 cm. The solid line is a linear fit with parameter values given in the plot.

4.2. Burnup as a function of enrichment

The fraction of particles that fails due to pressure buildup and weakening of the SiC layer depends on the fuel burnup (e.g., expressed in FIMA). Therefore, a relationship is required that relates the initial fuel enrichment and the final discharge

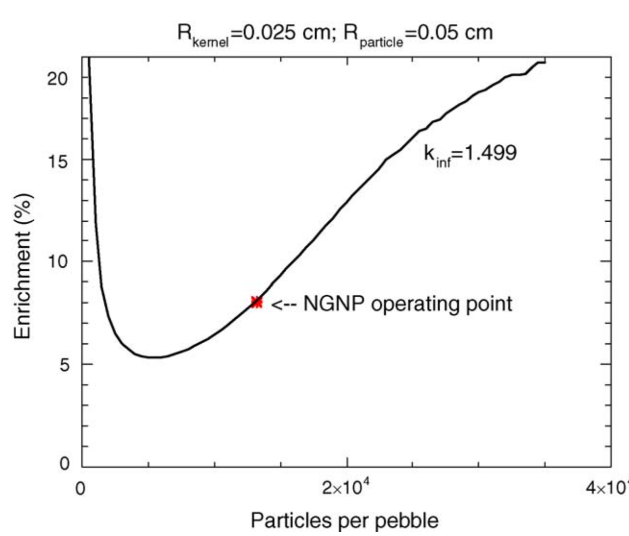

Fig. 4. The fuel enrichment as a function of the number of particles per pebble. Left of the minimum, the curve corresponds to the over-moderated region. Increasing the number of particles starting at the minimum reduces the moderator-to-fuel ratio, which would lead to a decrease of k_∞ if the fuel enrichment were not to be raised. The NGNP operating point refers to the pebble-bed VHTR design in development at the INL.

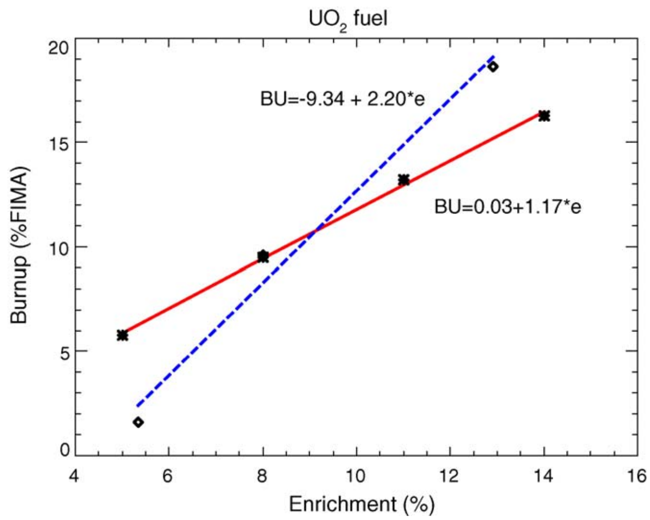

Fig. 5. Correlation for the final discharge burnup as a function of the initial fuel enrichment based on particle burnup calculations with SCALE (SCALE-5, 2005) (solid line) and full-core burnup calculations with PEBBED (Gougar et al., 2004) (dotted line). At 8% enrichment two points are drawn.

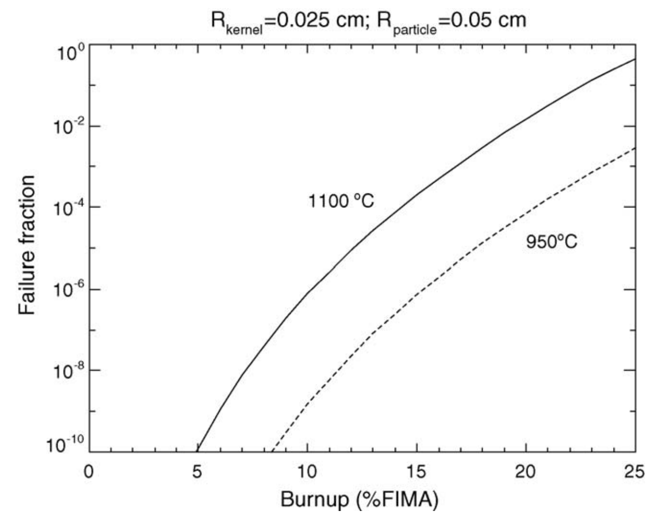

Fig. 6. The particle failure fraction as a function of the fuel discharge burnup with the fuel temperature as a parameter. Data have been sampled and reconstructed from ref. Nabielek et al. (2004).

burnup of the fuel. Of course, this relationship depends on the reactor type being considered and the fuel management scheme being applied. In this paper, first a simple approach is taken. For a single fuel particle, burnup calculations were performed with the SCALE code system (SCALE-5, 2005) and the k_∞ was determined at several time steps during the burnup. From these k_∞ values, and assuming that the final discharge burnup for the NGNP with 8% enriched fuel equals about 9.5% FIMA, the discharge burnup values for the other enrichments could be estimated. The correlation between enrichment and final discharge burnup is shown in Fig. 5 (solid line).

To include some of the important spectral effects that take place during burnup in a pebble-bed reactor with continuous refueling, as well as the spectral influence of the reflectors, three-dimensional calculations were performed with the PEBBED (Gougar et al., 2004) code for the PBMR-268 core design. For three enrichment values, the equilibrium core composition was calculated with a discharge burnup such that the effective multiplication factor equals 1.05, which allows enough excess reactivity for control of the reactor and for offsetting the poisoning by nuclides not explicitly taken into account. The results are shown in Fig. 5 (dashed line). Note that the point at 8% enrichment is the same as the SCALE result. Furthermore, it can be deduced that the reactor cannot become critical with initial fuel enrichment lower than approximately 4%. Because the solid line depends less on the actual core design, this curve is used in the further analysis.

4.3. *Failure rate as a function of fuel burnup*

Once the final discharge burnup is determined as a function of the initial fuel enrichment, the expected failure rate due to fuel burnup and weakening of the SiC layer can be obtained. For the purpose of this paper, some curves, published by others (Nabielek et al., 2004), calculated with the PANAMA code were sampled and fitted to a Weibull distribution for a particle with a SiC layer of 35 μm and an average midpoint radius of 0.04 cm. The curves are reconstructed in Fig. 6. Because they are valid only for fuel temperatures of 950 and 1100 °C and for particles with a kernel diameter of 0.05 cm and an outer diameter of 0.1 cm, our analysis is limited to these conditions as well. Furthermore, it is emphasized that the original curves were generated for irradiation conditions in the Petten High Flux Reactor, which might differ from those in an HTR. Especially the neutron spectrum might differ, which influences the amount of the fast neutron fluence ($E > 0.1$ MeV) on the SiC layer per unit of burnup. Clearly, extension of these curves to a wider range of temperatures and to other particle sizes under more HTR-like irradiation conditions has first priority in continuing these studies.

5. Calculations and results

The procedure to calculate the failure impact as a function of the particle packing, or likewise as a function of the fuel enrichment, is as follows.

First, the distribution of distances between nearest neighbor particles in the fuel zone of a pebble has to be calculated. This has been done for packing density values that range from 500 particles per pebble up to 35,000 with intervals of 500. Some examples of these distributions are shown in Figs. 1 and 2. Subsequently, the number of particles that touch each other is defined as the number of particles with nearest neighbors within a distance of 180 μm. Using the failure fraction for "touching" of 1.4×10^{-5}, the particle failure fraction for this process can easily be obtained.

Second, for each particle packing density, the fuel enrichment is determined that ensures the reactivity of the fresh fuel is preserved equal to the target reactivity. Subsequently, the final discharge burnup is estimated using a simple correlation derived from generic burnup calculations. These two steps have been

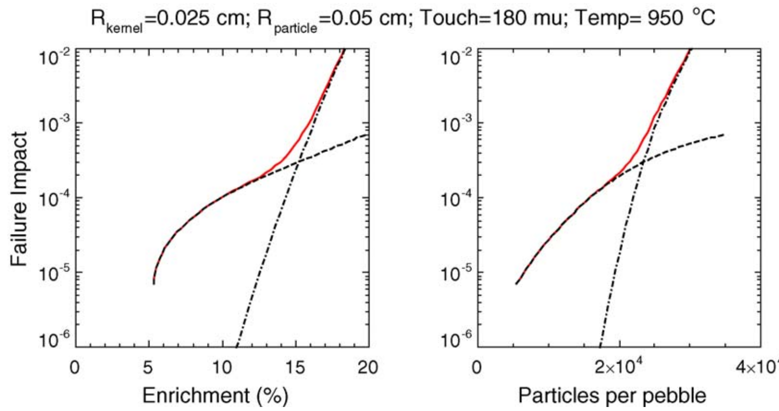

Fig. 7. Particle failure impact as a function of the fuel enrichment and the particle packing for a definition of "touching" of proximity to within 180 μm at a fuel temperature of 950 °C.

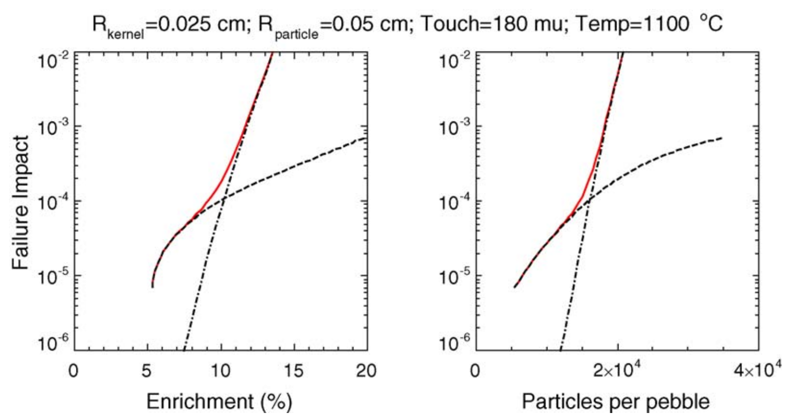

Fig. 8. Particle failure impact as a function of the fuel enrichment and the particle packing for a definition of "touching" of proximity to within 180 μm at a fuel temperature of 1100 °C.

described in Sections 4.1 and 4.2. Finally, the particle failure fraction due to pressure buildup and SiC deterioration is estimated using data from the literature.

The results for a fuel temperature of 950 °C are shown in Fig. 7. The dashed line gives the contribution due to "touching" in the manufacturing process, while the dot–dashed line is the failure rate due to pressure buildup in the buffer of the particle. The solid line shows the sum of the contribution to failure from the two processes. Although there is no clear minimum in the figures, it is clear that one should avoid high packing fractions and high values for the fuel enrichment, to avoid a high failure impact due to buildup of gaseous fission product and CO. The failure impact increases rapidly if the particle packing exceeds 30,000 particles per pebble.

Raising the fuel temperature increases strongly the failure fraction due to deterioration of the SiC layer. Fig. 8 gives the results for 1100 °C. It is emphasized that the definition of failure impact is quite arbitrary, and can certainly be improved, e.g. by taking into account explicitly the fission products that actually exist at an equilibrium concentration in the particle and the fission products that build up linearly with burnup. Nevertheless, we can use these results to see how the particle packing and the fuel enrichment of the 1100 °C cases should be adapted in order not to exceed the failure impact of the corresponding 950 °C cases. For example, the failure impact at 950 °C and a particle packing of 20,000 particles per pebble equals about 2×10^{-4}, while for the same failure impact, the particle packing at a temperature of 1100 °C should not exceed 15,000 particles per pebble with a corresponding fuel enrichment of about 10%.

If the enrichment versus burnup dependence is used that is given by the dashed line in Fig. 5, then the failure impact due to pressure buildup in the buffer of the particle increases for enrichments above 8%, while it decreases for lower burnup values. This implies that the dot–dashed lines in Figs. 7 and 8 would become even steeper. Clearly, it is very important that the actual core design be used in any quantitative analysis aimed at establishing the final discharge burnup that can be achieved for a certain fuel design.

6. Conclusions

The particle failure impact depends mainly on two mechanisms: touching of particles during the isostatic pressing stage in the pebble manufacturing process, and the buildup of gaseous products and subsequent malfunctioning of the SiC layer during the irradiation of the pebble. The first effect requires the distribution function of the distance between the centers of the particles. For this, the Poisson distribution may only be used if the particles are very small (see Fig. 1). For standard fuel particles with radius of 0.05 cm the Poisson distribution is not valid and a numerical approach should be used. However, if the critical distance below which particles are deemed touching is increased, say to 180 μm, the Poisson distribution is valid within 25% for a packing density of 15,000 particles per standard fuel pebble. The limit of 180 μm is used in this paper as it fits best to experimental data on German-made fuel pebbles (Nabielek et al., 2004).

At low packing fraction, the particles touching during the pressing stage dominate the particle failure rate, but with relatively mild consequences for the failure impact. On the other hand, at high particle density, the buildup of gaseous products may lead to relatively high values of the failure impact. With increasing fuel temperature, this effect becomes even more pronounced due to deterioration of the SiC layer, which shifts the failure probability curves to higher value (see Fig. 6). This means that the failure impact increases strongly with fuel temperature as well. For the same particle failure impact at elevated operating temperatures, the final discharge burnup should be reduced. If the initial reactivity of the fuel is to be preserved, this means one can reduce both the fuel enrichment and the number of fuel particles per pebble.

Clearly, the results and conclusions of this paper can only be preliminary, and much remains to be done. The most important improvements should be made to the failure probability curves shown in Fig. 6. These should be generated for circumstances more applicable to HTRs, and should be extended to a wider range of fuel temperature and particle sizes. This is especially true as this process of particle failure gains importance with increasing fuel temperature. Furthermore, the temperature of the fuel and the final discharge burnup should be representative for the reactor under consideration. This means that coupled neutronics/thermo-hydraulics calculations should be performed to obtain the temperature history of each batch of pebbles flowing multiple times through the core, and that the failure probability should be calculated for the various temperature histories weighted with the number of pebbles following each history. For this purpose, it is foreseen to couple the improved particle failure models to the PEBBED code (Gougar et al., 2004). To extend the model to other particle sizes, the failure model for particle cracking during the manufacturing process should be extended. After these improvements, an optimization study could be undertaken to determine the fuel design that minimizes the fuel failure rate at higher operating temperatures as envisaged in VHTR designs like the Next Generation Nuclear Plant at INL.

At its inception, this study was meant to help support the planning, design and conduct of fuel irradiation experiments. Clearly, while not drawing conclusions as regard to the actual design of a fuel test, the results obtained in this paper can be of direct use for that purpose.

Finally, though not initially part of the goals of this study, it is clear that the implications of the relationship between a chosen operating temperature, selected fuel enrichment and a design packing density will have a significant impact on the failure fraction of the fuel design. This study can easily be extended to include prismatic block fuel concepts.

Acknowledgements

This work was performed in part during a sabbatical leave of the second author (J.L.K.) at INL in the summer of 2005. He acknowledges INL for hosting and supporting him during this visit. Furthermore, the authors acknowledge Dr. David Petti and Dr. John Maki of INL for sharing their experience about fuel performance models. This work was supported in part by a U.S. Department of Energy Nuclear Energy Research Initiative (NERI) project (project NERI-02-195) and in part under the NGNP Project, both under the auspices of the Department of Energy, Office of Nuclear Energy, Science and Technology, under DOE Idaho Operations Office Contract DE-AC07-99ID13727.

References

Bell, G.I., Glasstone, S., 1970. Nuclear Reactor Theory. Van Nostrand Reinhold Company, New York.

Bende, E.E., Hogenbirk, A.H., Kloosterman, J.L., Van Dam, H., 1999. Analytical calculation of the average Dancoff factor for a fuel kernel in a pebble-bed high temperature reactor. Nucl. Sci. Eng. 113, 147–162.

Martin, D.G., 2001. Considerations pertaining to the achievement of high-burnups in HTR fuel. Nucl. Eng. Des. 213, 241–258.

de Kruijf, W.J.M., Kloosterman, J.L., 2003. On the average chord length in reactor physics. Ann. Nucl. Energy 30, 549–553.

Petti, D., Martin, Ph., Phelip, M., Ballinger, R.G., Development of Improved Models and Designs for Coated Particle Gas Reactor Fuels, I-NERI, INEEL/EXT-05-02615, December 2004.

Duderstadt, J.J., Hamilton, L.J., 1976. Nuclear Reactor Analysis. John Wiley and Sons, New York.

Evans, R.D., 1955. The Atomic Nucleus. McGraw-Hill, New York.

Gougar, H.D., Terry, W.K., Ougouag, A.M., 2004. PEBBED User's Manual. Idaho National Laboratory, Idaho Falls, USA.

MacDonald, P.E., et al., NGNP Preliminary Point Design—Results of the Initial Neutronics and Thermo Hydraulics Assessments, INEEL/EXT-03-00870-Rev 1, Idaho National Laboratory, Idaho Falls, USA, 2003.

Nabielek, H., Verfondern, K., Werner, H., 2004. Can we predict coated particle failure? A conversation on CONVOL, PANAMA and other codes. In: Technical Meeting on the Current Status and Future Prospects of Gas Cooled Reactor Fuels, Vienna, June 7–9.

SCALE-5, Modular Code System for Performing Standardized Computer Analysis for Licensing Evaluations, Oak Ridge National Laboratory, Tennessee, USA, 2005.

Wang, J., Ballinger, R.G., Maclean, H.J., 2004. TIMCOAT: an integrated fuel performance model for coated particle fuel. Nucl. Technol. 148, 68–96.

Zweifel, P.F., 1973. Reactor Physics. McGraw-Hill, New York.