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# Performance analysis of TRISO coated fuel particles with kernel migration

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## Abstract

High temperature reactors (HTRs) are among the candidates of the possible next generation nuclear plant. HTRs are expected to offer attractive features such as inherent safety, low cost of electricity generation, and short construction period. The safety performance of high temperature gas cooled reactors mainly relies on the quality and integrity of the coated fuel particles. One of the possible failure mechanisms for TRISO coated fuel particles is kernel migration, in which the fuel kernel migrates through the buffer layer due to the overall high temperature gradient and the carbon monoxide formation. In this study, thermal and mechanical performances of a coated fuel particle with a migrated kernel are analyzed by the finite element technique. Calculations are performed for two different operating conditions represented by two different surface temperatures. Similar analyses are also carried out for a nominal particle without kernel migration for comparison. Temperatures and stress distributions are calculated and failure probabilities of the coated fuel particle are obtained based on the Weibull statistics. Further comparison is made in terms of the failure probability considering a coated fuel particle whose inner pyrolitic carbon layer is defective or already failed. Furthermore, stress distributions for the particle with kernel migration through the inner pyrolytic carbon layer has been obtained. Calculated temperature distributions, maximum stress values, and failure probabilities are reported to assess the influence of kernel migration on coated fuel particle behavior. Results show that high temperature operation, high burnup, and excessive temperature gradient on the fuel particle can lead to fuel failure. The pressure vessel failure is generally observed well before the failure by the kernel migration. In fact, these failure modes are interrelated and affect each other.

## 1. Introduction

HTR safety is closely related with the integrity of the coated fuel particle (CFP). The current design fuel, TRISO coated fuel particle, is composed of the kernel, the buffer, the inner pyrolytic carbon (IPyC) layer, the silicon carbide layer (SiC), and the outer pyrolytic carbon layer (OPyC).

The kernel contains nuclear fuel and its composition during the operation controls the basic chemistry of the coated fuel particle. The kernel material is commonly $UO_2$. Other kernel designs with $PuO_2$, $ThO_2$, UCO, $UC_2$, and their mixtures are also under consideration. Basic functions of the kernel are to control the internal pressure and migration potential by holding down the CO production and binding rare earths as oxides to limit their migration to the coating layers as well as producing the desired power.

The buffer is a porous layer surrounding the kernel and made of low density pyrolytic carbon. The buffer layer captures fission product recoils and protects the IPyC from radiation damage. Its porous design provides free volume for fission product gases and controls the internal pressure. The buffer layer can be deformed easily to accommodate kernel swelling [1].

The inner pyrolytic carbon layer is a high density carbon layer deposited on the buffer. It provides a smooth surface for SiC deposition during the manufacturing of the fuel particle and protects the kernel from the chlorine liberated

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during the SiC coating process. The IPyC and OPyC layers act as barriers against the fission product release out of the particle. They are also expected to keep the SiC layer under compression during power operation so that pressure vessel failure can be avoided.

The SiC layer is the primary pressure boundary and fission product barrier in the coated fuel particle. It provides structural support to accommodate internal gas pressure. SiC is a brittle material and assumed to release fission products only when failed.

Fission product gases released out of the kernel and CO produced due to liberated oxygen result in stress build-up on coating layers as the burnup proceeds. However, the IPyC and OPyC layers also undergo irradiation induced shrinkage as a result of fast neutron exposure. Consequently, both layers contract resulting in reduced tensile stress inside the SiC layer. Due to the anisotropy in the pyrocarbon layers, the shrinkage behaviour differ in radial and tangential directions. The shrinkage in radial direction reverses to swelling during early stages of burnup while shrinkage in the tangential direction persists. Increased tensile stress on the SiC layer may cause pressure vessel failure in the coated fuel particle. The presence of a flaw inside the coated layers and manufacturing defects play important roles in the integrity of the SiC layer.

Early studies on coated fuel particle stress analysis include simplified mathematical models of Prados and Scott [2] and Kaae [3] for calculating stress distributions inside layers. Martin's model [4,5] is utilized in the STRESS3 code which performs pressure vessel failure analysis and when used with the statistical code STAPLE takes changes in particle parameters and their effects on the failure probability into account. Nabielek et al. [6] developed the PANAMA code which calculates the stress distribution for the SiC layer with the thin shell approximation and the CONVOL code which uses an analytical solution based on a Weibull distribution for the SiC strength and the normal distribution for kernel and buffer layer thicknesses. Miller et al. at the Idaho National Laboratory have developed an integrated mechanistic fuel performance code, PARFUME, which performs multi-dimensional mechanical analysis by finite element techniques, thermal analysis and statistical calculations [7]. This code is capable of making analyses for different cases such as shrinkage cracking, partial debonding, asphericity, kernel migration, and SiC thinning [8–10]. Another CFP thermal and mechanical analysis code, ATLAS, has been developed by CEA in partnership with FRAMATOME. The ATLAS code is capable of performing thermal, mechanical, and statistical calculations with the finite element technique [11]. Korea Atomic Energy Research Institute's CFP analysis code, COPA, can perform thermal and mechanical analyses as well as calculate failure probabilities. COPA considers fuel failure mechanisms such as pressure vessel failure, crack induced failure, SiC degradation, and kernel migration [12].

Coated fuel particles may fail as a result of kernel migration, fission product chemical attack on SiC, yielding of the SiC layer, thermal decomposition, and debonding of the layers. The objective of this study is to analyze the effect of kernel migration on temperature and stress distributions in the CFP by the finite element analysis method. The advantage of the finite element method is the capability to analyze multi-dimensional loading in complex geometries. The finite element analysis of the coated fuel particle can be utilized for complex cases such as deviations from sphericity and predict multi-dimensional effects without simplifications. Statistical variations in the model input parameters can also be incorporated with finite element calculations. The results of this study are expected to be useful for evaluating safety characteristics of coated fuel particles subjected to kernel migration under different operational conditions.

## 2. Kernel migration

Kernel migration is simply defined as the movement of the kernel towards TRISO coated layers. The driving force for the kernel migration is extreme operating conditions and asymmetrical kernel production during manufacturing [13]. This so-called 'amoeba effect' strongly depends on power density, temperature, and temperature gradient across the fuel. Therefore, prismatic fuel elements have a greater susceptibility for kernel migration compared to pebble bed reactor fuel elements due to the presence of a more severe temperature gradient [14].

In oxide based fuel kernels, free oxgen is formed as a result of the consumption of fissionable nuclides. This free oxygen first oxidizes the rare earth elements which have the greatest affinity for oxygen. The remaining oxygen oxidizes the other elements such as Sr, Eu, Zr, and Ba in $UO_2$ fuels. If there is still free oxygen remaining in the system, it may react with the carbon in the coating layers under appropriate conditions resulting in CO and $CO_2$ production. CO and $CO_2$ formation can be avoided by limiting the free oxygen present in the kernel. In the case of $UO_2$, the lowest charge state of uranium is +4. It is the common charge state of uranium in the fresh fuel and it is more difficult to oxidize uranium to higher charge states than oxidizing other constituents of the fuel. On the other hand, hypostoichiometric mixed oxide fuel kernels obtained by mixing +3 and +4 valanced Pu will not be susceptible to $CO/CO_2$ formation until very high burnup levels since oxygen liberated with fission reactions will be preferentially oxidizing plutonium to its +4 charge state. There are other remedies such as placing a getter in or near the kernel to bind the excess oxygen and making a two-phase kernel such as UCO, i.e., a mixture of $UO_2$ and $UC_2$, allowing the released oxygen to react with the carbide phase without diffusing through the kernel [1].

Kernel migration has been studied experimentally by Lindemer et al. for different types of HTR fuels [15] and analytically by Choi and Lee, who considered interactive transport between CO gas flow and diffusion of oxygen atoms [16].

It has been suggested [17] that $CO_2$ formation is limited and its contribution towards the gas mixture is below a few percent. Therefore, only CO is assumed to be formed in this study due to the reaction of excess free oxygen with carbon in the buffer. This CO contributes to the pressure inside the coated fuel particle layers together with the gaseous fission products released from the kernel.

Temperature gradients resulting from extreme operating conditions of coated fuel particles lead to carbon transport from the hotter side to the colder side of the IPyC layer. This causes an effective movement of the kernel in the opposite direction, called kernel migration. Experiments on this amoeba effect were carried out by capsule irradiation at a temperature gradient of 15000 °C/m and temperatures up to 1700 °C [18]. In these experiments, no coated particle failure has been observed and the maximum extension of kernel migration was less than 55 μm. This observation indicates that the kernel migration is confined within the buffer layer for this set of experiments. Results of irradiation tests gathered by Fukuda et al. on kernel migration distances lead to the following correlation, which is valid for the temperature gradient of 15000 °C/m [18]:

$$\mathrm{KMR} = 2 \times 10^{-6} \exp\left(-\frac{14800}{T}\right) \frac{1}{T^2} \frac{\mathrm{d}T}{\mathrm{d}r}, \tag{1}$$

where $r$ is the radial distance in meters, $T$ is the temperature in Kelvins and KMR is the kernel migration rate in m/s. Eq. (1) is employed in the present study to evaluate the position of the kernel as a function of temperature subjected to kernel migration. Therefore, fuel and operational parameters utilized in this study represent a typical coated fuel particle utilized in the Japanese test reactor HTTR.

The fuel kernel travels up the temperature gradient inside the buffer at the first stage of kernel migration. At this stage, carbon removal due to oxidation as well as compaction due to mechanical effects may be observed within the buffer layer at the migration front. Once the kernel reaches the IPyC layer, it is expected to migrate inside the IPyC with a slower rate due to increased carbon density in this layer. Since the IPyC layer has load bearing capability, a decrease in the layer thickness may result in premature failure of the IPyC layer. Then, the stress acting on the SiC layer becomes tensile and increases with increasing burnup. The SiC layer will also be susceptable for chemical interactions with oxygen and fission products at this stage of kernel migration.

The present study includes thermal and mechanical analyses of a TRISO coated particle with a migrated kernel using finite element techniques. Since the geometry of simple concentric spheres is not preserved upon kernel migration, it is not feasible to calculate temperature and stress distributions using analytical techniques.

## 3. Modelling

Fuel behavior analysis upon kernel migration in a CFP is performed by the finite element analysis code ANSYS. The analysis is composed of thermal and mechanical parts as well as predicting the failure probability of the particle. Table 1 presents the properties of the TRISO particle under consideration in this study.

Table 1
Basic characteristics of a TRISO particle [19]

| | |
|---|---|
| Fuel material | $UO_2$ |
| Oxygen to uranium ratio | 2 |
| Kernel density | 10.5 g/cm$^3$ |
| Kernel diameter | 600 μm |
| Coating layer materials | PyC/PyC/SiC/PyC |
| Coating layer thicknesses | 60/30/25/45 μm |
| Coating layer densities | 1.01/1.85/3.20/1.85 g/cm$^3$ |

The CFP is assumed to produce a power of 0.3 W power in a typical kernel. The outer surface temperatures of the CFP are taken to be 1473 K and 1723 K for the two cases considered in this study. Both surface temperatures are within the normal operating range of HTTR. The higher one is close to the limiting temperature and the burnup limit for this case is 8% FIMA which is higher than the target burnup of the HTTR [19]. A temperature gradient of 15000 °C/m is assumed to be present on the particle in order to simulate kernel migration conditions. This temperature gradient has been applied to measure kernel migration distances in HTTR fuel [18]. The finite element model is composed of the kernel, buffer, IPyC, SiC, and OPyC. A CO filled gap between the kernel and the buffer is included to represent the movement of the migrated kernel. The model is two dimensional and axisymmetric. Fig. 1 presents the finite element model mesh structure of the coated fuel particle with a migrated kernel.

Kernel migration calculations start with the calculation of the temperature distribution inside a nominal coated

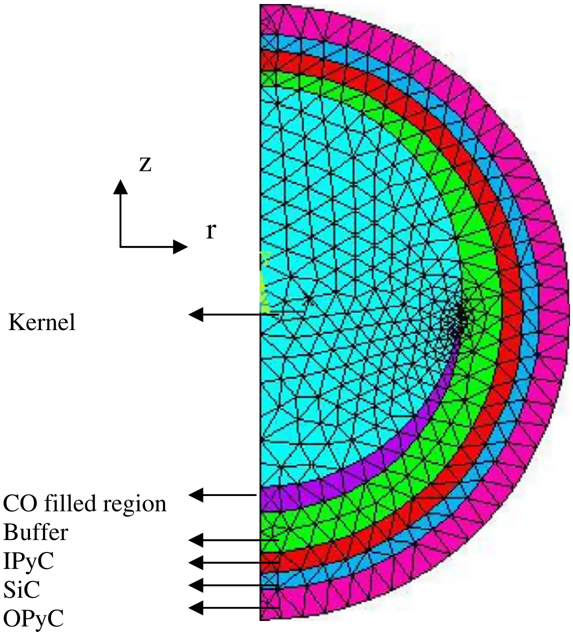

Fig. 1. Finite element model of the coated fuel particle with a migrated kernel.

fuel particle. The maximum kernel temperature value is employed in the calculation of the kernel migration distance for the next time step. This choice yields the most conservative results from the nuclear safety point of view. The kernel is assumed to migrate along the *z*-axis and a displacement equal to the kernel migration distance calculated from Eq. (1) is applied on the kernel. The kernel is assumed to preserve its spherical shape during the kernel migration for calculations. A new temperature distribution is obtained and a new migration distance is calculated for the next time step. Time steps are chosen small enough so that further reduction will not change the results. All of the free oxygen formed as a result of fission is assumed to bind the carbon from the buffer layer to form CO and CO gas is assumed to fill the gap left behind the migrated kernel. The maximum temperature value is also employed for the calculation of the fission gases and CO pressure inside the IPyC layer. The number of fission gas atoms diffused out of the kernel and the number of CO molecules formed inside the CFP are calculated at each time step. Fission product gases Xe, Kr, and CO molecules are assumed to fill the free volume of the buffer and the gap left behind the kernel after migration. Moreover, kernel swelling is also taken into account in the calculation of the free volume available for the gas molecules. Ideal gas equation of state is employed for the calculation of pressure inside the IPyC layer. The Redlich–Kwong equation, which is applicable to some HTR fuel operating conditions [21], is found to be not fully applicable for the whole irradiation period of the two cases. Stress distributions for the load bearing layers are obtained at each time step using the internal gas pressure calculated at each time step as the boundary condition on the inner surface of the IPyC layer. The calculated maximum tangential stress value is then employed to evaluate the failure probability of the coated fuel particle at each time step.

### 3.1. Thermal analysis

Thermal analysis involves calculation of the nodal temperatures at specified time steps up to the desired burnup. The maximum kernel temperature value is employed for calculating the kernel migration distance for each time step. Therefore, it is expected to yield a conservatively larger kernel migration distance. CO and fission product gases are assumed to accumulate in the open volume between the kernel and the buffer on one side, against the large scale temperature gradient. The presence of such a gas-filled region causes a greater temperature gradient within the particle along the migration direction compared to that in the transverse direction.

### 3.2. Mechanical analysis

Mechanical analysis of the coated fuel particle involves the calculation of radial and tangential stresses for each layer and prediction of the failure probability of the particle. Fission gases and CO build-up inside the kernel and buffer regions as the burnup proceeds. IPyC, OPyC, and SiC layers act as load bearing barriers. The IPyC and OPyC layers both shrink and creep during irradiation whereas the SiC layer experiences only elastic deformation during this process. Gas pressure itself causes tensile tangential stress in the SiC layer while IPyC and OPyC layers may cause tensile or compressive stresses in the SiC layer. Due to the pyrocarbon shrinkage and swelling, radial and tangential deformation histories differ [7]. The mechanical model used throughout this study takes anisotropy and creep of pyrocarbon layers into account. The mechanical properties of layers employed in the analysis are presented in Table 2 [22]. Internal pressure build-up due to the fission product gas release and CO formation is also calculated during the analysis. The tangential and radial swelling rates employed in the analysis for pyrolytic carbon layers are obtained from the following equations [22]. PyC radial swelling rate is

$$\begin{aligned}(\Delta L/L) = {} & 4.52013 \times 10^{-4}x^5 - 8.36313 \times 10^{-3}x^4 \\ & + 5.67549 \times 10^{-2}x^3 - 1.74247 \times 10^{-1}x^2 \\ & + 2.62692 \times 10^{-1}x - 1.43234 \times 10^{-1}. \end{aligned} \tag{2}$$

PyC tangential swelling rate is

$$\begin{aligned}(\Delta L/L) = {} & 1.30457 \times 10^{-4}x^3 - 2.10029 \times 10^{-3}x^2 \\ & + 9.07826 \times 10^{-3}x - 3.24737 \times 10^{-2}, \end{aligned} \tag{3}$$

where $x$ is the fast neutron fluence ($10^{25}$ n/m$^2$) for $E > 0.18$ MeV. It should be noted that swelling and shrinkage properties are extremely material dependent and posses significant uncertainties.

Stable gaseous fission products, xenon and krypton, comprise 31% of the fissions. Diffusion of these gases are assumed to be well represented by the Booth equivalent sphere release model [23] and this model is used explicitly in this study. The fractional release of Xe and Kr vary from 50% to 90% for the cases analyzed as a function of the kernel temperature. These release fractions are calculated based on diffusion calculations using the simple Booth model.

Free oxygen released from the kernel immediately reacts with the carbon in the buffer and forms CO and a few percent of $CO_2$. The following experimental correlation of oxygen release [17] is employed in this study to calculate the amount of CO formed inside the IPyC layer:

$$\log\left\{(O/f)/t^2\right\} = -0.21 - 8500/(T + 273), \tag{4}$$

Table 2
Material properties for pyrocarbon and SiC layers [19,21]

| | |
|---|---|
| PyC modulus of elasticity (MPa) | $3.96 \times 10^4$ |
| PyC Poisson's ratio | 0.33 |
| PyC coefficient of thermal expansion ($K^{-1}$) | $5.50 \times 10^{-6}$ |
| PyC creep coefficient (MPa – $10^{25}$/m$^2$)$^{-1}$, $E > 0.18$ MeV | $4.93 \times 10^{-4}$ |
| SiC modulus of elasticity (MPa) | $3.70 \times 10^5$ |
| SiC Poisson's ratio | 0.13 |
| SiC coefficient of thermal expansion ($K^{-1}$) | $4.90 \times 10^{-6}$ |

where $O/f$ is the oxygen release at the end of irradiation (atoms per fission), $t$ is the irradiation time in days and $T$ is the time-averaged particle surface temperature during irradiation in °C.

The upper limit of the $O/f$ value is given by the stochiometric formula [17]

$$O/f = 0.4 \cdot f_{\mathrm{U}} + 0.85 \cdot f_{\mathrm{Pu}}, \tag{5}$$

where $f_{\mathrm{U}}$ is the ratio of the number of uranium fissions to the total number of fissions, and $f_{\mathrm{Pu}}$ is $(1 - f_{\mathrm{U}})$. $f_{\mathrm{Pu}}$ is estimated as two times the burnup in FIMA units [24].

The ideal gas law is employed to calculate the pressure on the inner side of the IPyC layer as a function of burnup. The free volume on the inner side of the IPyC consists of the empty volume of the buffer, which is 50% of the fully dense material, and the free volume created by CO formation within the buffer which is small compared to the other. On the other hand, this free volume is compensated by the swelling of the kernel, which is assumed to be 0.47% per %FIMA [23].

The stress distributions in IPyC, SiC, and OPyC, layers are calculated for CFPs with nominal and migrated kernels for two representative cases with different surface temperatures. The boundary conditions employed on the relevant surfaces are the calculated internal pressure and an ambient pressure of 0.1 MPa. Creep, swelling, and shrinkage behavior of the pyrocarbon layers are also included in the analysis. The anisotropic behavior of IPyC and OPyC layers is taken into consideration in predicting the swelling/shrinkage behaviour of those layers.

The failure probability of the TRISO particle depends on burnup and internal gas pressure. It is assumed that crack extension and fracture are observed in case of tensile loading. The cumulative failure probability for each coating layer is expressed by a Weibull distribution with Eq. (6)

$$f(t) = 1 - \exp\left\{ -\ln 2 \times \left( \frac{\sigma(t)}{\sigma_0} \right)^m \right\}, \tag{6}$$

where $f(t)$ is the failure probability of the layer at irradiation time $t$, $\sigma(t)$ is the stress on the layer at irradiation time $t$, $\sigma_0$ is the median strength of the layer and, $m$ is the Weibull modulus of the layer. $\sigma_0$ values for the pyrocarbon layers and SiC are 200 MPa and 873 MPa, respectively. Values used for the Weibull moduli for the pyrocarbon and SiC layers are 5.0 and 8.02, respectively [20].

The general approach in the integrity analysis of the particle involves predicting the failure probability of each individual layer. Failure probabilities for a thinned and a failed IPyC layer are also calculated to evaluate the contribution of the IPyC. Only SiC failure mode is assumed in the analysis.

## 4. Results

The main goal of this study is to develop a methodology to analyze TRISO coated fuel particle performance in case of kernel migration. As mention earlier, the correlation, (Eq. (1)), used in this study is based on observations of kernel migration confined within the buffer layer. In order to get some idea about the further progress of kernel migration, typical burnup and pressure values at each burnup are estimated for the kernel that reached the interface between the buffer and the IPyC. These critical values are given in Table 3 for different surface temperatures. These predictions are based on thermal calculations, the $(O/f)$ ratio, fission gas release predictions, and pressure predictions based on the ideal gas law. The burnup value for transversing through the buffer layer in the highest temperature case is well above the typical design burnup. As the kernel temperature is lowered, kernel migration into the IPyC is significantly delayed. Meanwhile, the pressure build-up becomes significant enough to increase the probability of pressure vessel failure considerably.

Fig. 2 presents the temperature distribution inside the coated fuel particle at the end of 18% FIMA burnup. Total kernel migration distance is calculated to be 30 μm for the particle with 1473 K surface temperature at this burnup. For the particle with 1723 K surface temperature, kernel migration distance is calculated to be 43 μm. Fig. 3 shows the change of kernel migration distance as a function of burnup for the two cases. In both cases, the kernel migration is confined within the buffer layer even when the burnup significantly exceeds the operational burnup limit.

Table 3
Critical burnup and pressures for the kernel to reach the IPyC layer

| Temperature (K) | Burnup (%FIMA) | Gas pressure (MPa) |
|---|---|---|
| 1423 | 47 | 314 |
| 1523 | 27 | 293 |
| 1623 | 17 | 155 |
| 1723 | 12 | 95 |

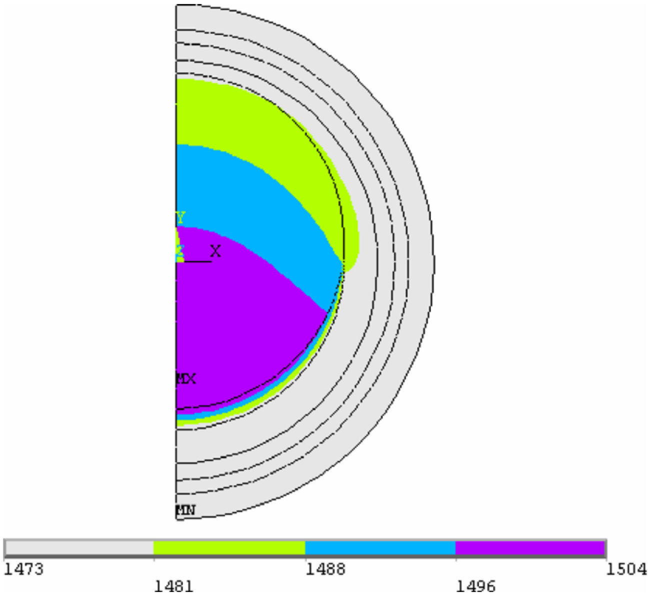

Fig. 2. Temperature distribution inside the coated fuel particle.

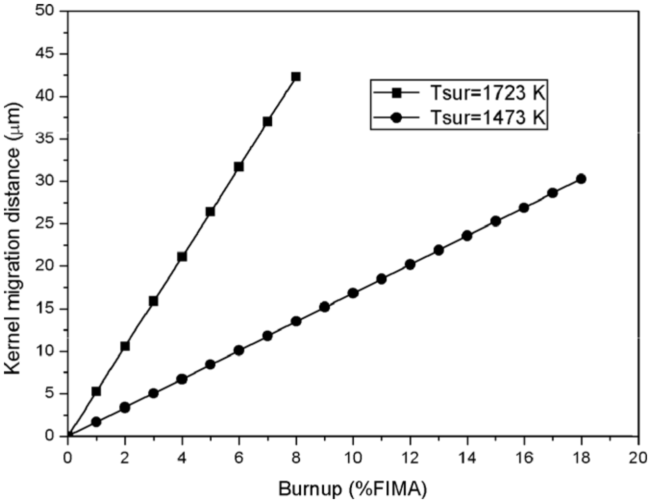

Fig. 3. Change of kernel migration distance with burnup.

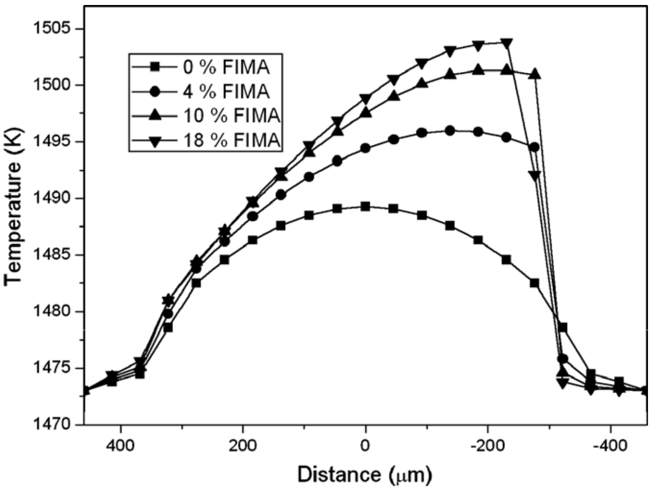

Fig. 5. Temperature distribution along the *z*-direction for 1473 K surface temperature.

The kernel is assumed to migrate along an axis and an asymmetry in the temperature distribution along the axial direction is observed as a result of the loss of concentricity. Due to relatively low heat conduction of the CO gas, the heat transfer is poor on the opposite direction of kernel migration. This results in increased temperatures near the gap. Fig. 4 shows the change in this asymmetric temperature distribution along the axial direction *z* at several burnup steps for a particle with 1723 K surface temperature. Fig. 5 presents the same distributions for a particle with 1473 K surface temperature. For both particles, the maximum kernel temperature is about 15–20 K greater than that for the unmigrated particle, which is of the same order of magnitude as the large scale temperature gradient. This local gradient may cancel out the effect of the large scale gradient on gas movement and may slow down, stop or even reverse the direction of migration of the kernel. For the particle with 1473 K on the surface, the maximum temperature reaches 1503 K. For the particle with 1723 K surface temperature, the maximum temperature is 1755 K. The temperature distributions along the direction perpendicular to the migration for the two cases are given in Figs. 6 and 7. A significant change in the temperature distribution is also observed for the transverse direction as the the kernel migrates. However, the slope is not as steep as it is in the direction of kernel migration.

Figs. 8 and 9 show the change of internal pressure with burnup inside the IPyC layer for a kernel migrated particle having 1723 K and 1473 K surface temperatures, respectively. The CO contribution towards the total internal pressure is dominant at the high temperature case due to the greater oxygen release promoting CO formation with increasing fuel burnup. By contrast, fission product gases are main contributers up to a burnup level of about 16% FIMA due to a rather limited oxygen release for the low temperature case.

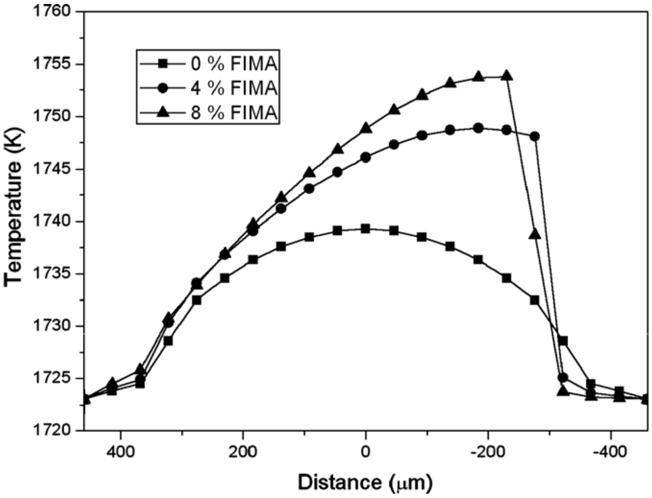

Fig. 4. Temperature distribution along the *z*-direction for 1723 K surface temperature.

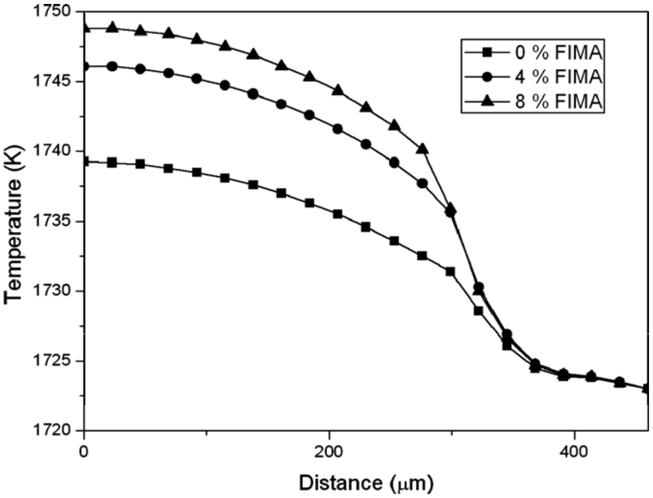

Fig. 6. Temperature distribution along the *r*-direction for 1723 K surface temperature.

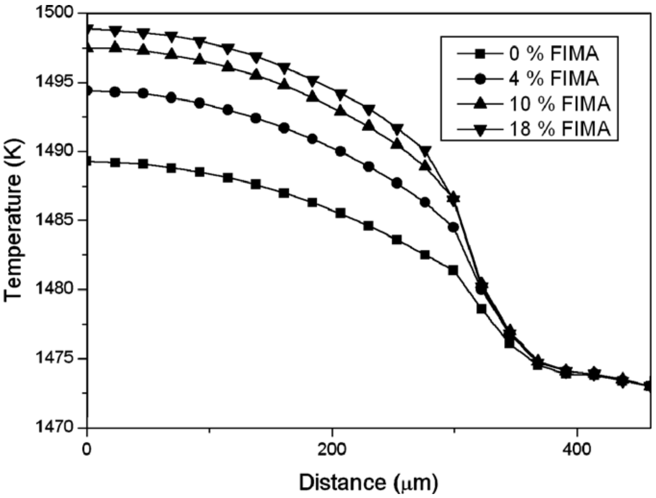

Fig. 7. Temperature distribution along the *r*-direction for 1473 K surface temperature.

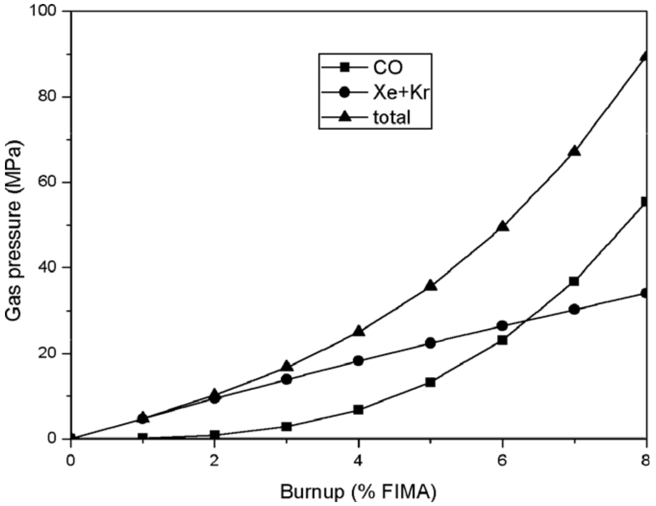

Fig. 8. Internal gas pressure for the case with 1723 K surface temperature.

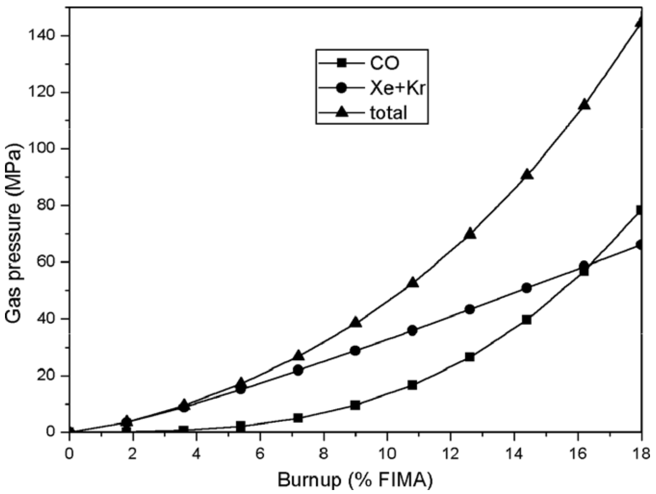

Fig. 9. Internal gas pressure for the case with 1473 K surface temperature.

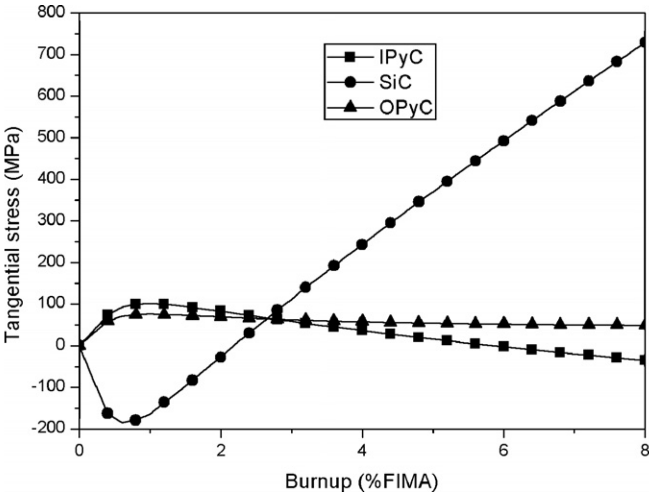

Fig. 10. Maximum tangential stress in the CFP with surface temperature of 1723 K.

Fig. 10 shows the variation of tangential stress as a function of burnup in three load bearing layers for a particle with surface temperature of 1723 K. The IPyC and OPyC layers shrink at the initial stages of the irradiation, keeping the SiC layer under compression. This condition persists until 2.4% FIMA burnup. Due to the relaxation in pyrolitic carbon layers in the following period, the tangential stress on SiC becomes tensile and increases continously with increasing internal pressure. Fig. 11 shows the same distribution for the particle with surface temperature of 1473 K. The initial compression period on SiC is preserved until the burnup of 4.2% FIMA, and then, the mean failure stress is reached at about a burnup of 17% FIMA.

Finite element calculations are also performed for a CFP without kernel migration with the same surface temperatures considered above for comparison. The maximum gas pressure inside the IPyC differs by only a few MPa's from those presented in Figs. 8 and 9. This is mainly due

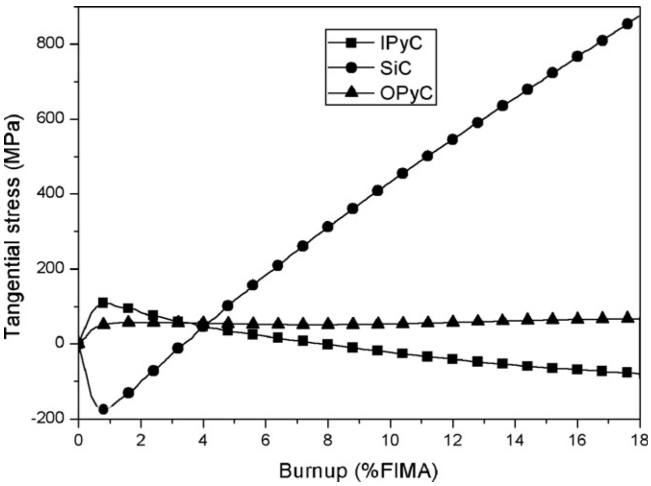

Fig. 11. Maximum tangential stress in the CFP with surface temperature of 1473 K.

to the small increase in gas temperature caused by kernel migration. Furthermore, the free volume left behind the migrated kernel is relatively small compared to the total empty volume. Since the pressure histories do not differ significantly, stress distributions are also similar for CFPs with and without kernel migration.

In the second part of the study, the effect of kernel migration is considered in coated fuel particles with a defective IPyC layer. The next analysis involves the evaluation of maximum stress values in the SiC layer and the corresponding failure probabilities for a TRISO CFP with a failed IPyC layer. This case may be viewed as a scenario of common mode of failures. The IPyC layer fails at the initial stages of operation due to increased tangential stress combined with a manufacturing defect. The finite element model, shown in Fig. 12(b) is constructed assuming a fully developed circumferential crack across the IPyC layer. The IPyC layer has no load bearing capability due to the crack. The finite element model includes all layers and the internal pressure is applied on the inner surface of the failed IPyC as a boundary condition. Calculations are carried out for the higher surface temperature case. The maximum tangential stress values as a function of burnup in the SiC layer are presented in Fig. 13 as the 'failed IPyC' case. The absence of IPyC support on the SiC results in the exertion of higher tensile stress and the stress reversal takes place at a lower burnup compared to that for the intact particle.

Another analysis involves the prediction of stress distribution inside the SiC layer for the case of defective IPyC containing a thin section. The kernel migration is still confined within the buffer layer. Otherwise, the burnup necessary for the penetration of the kernel up to the buffer-IPyC boundary is so high that pressure vessel failure is expected in advance. Pressure build-up due to CO formation as well as fission product release is significant at high burnups. Fig. 12(a) shows the finite element model of coating layers with a thin IPyC layer section of 15 μm, one half of the nominal thickness.

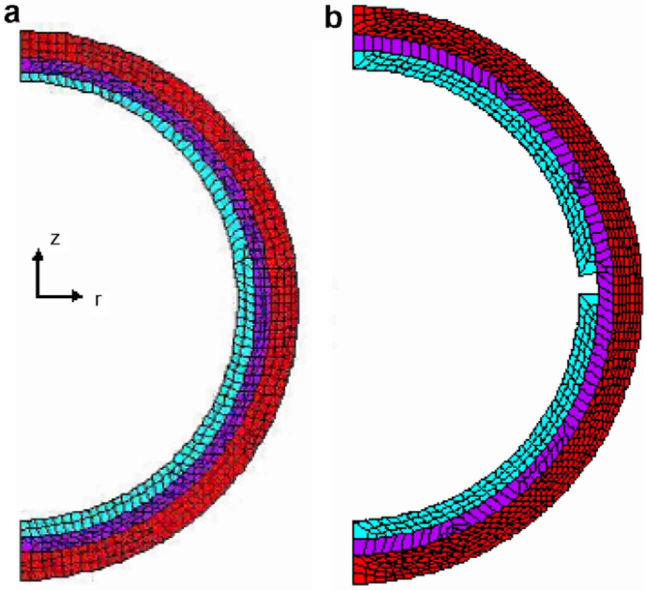

Fig. 12. Finite element model of the CFP with (a) thin and (b) failed IPyC.

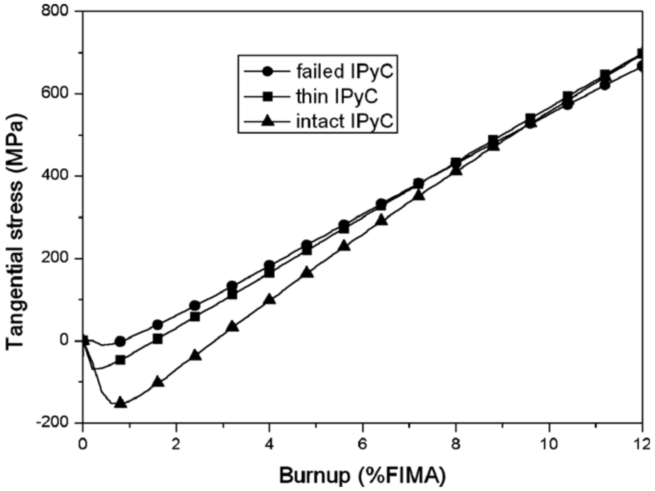

Fig. 13. Maximum tangential stress in the SiC with failed, thin and intact IPyC layers.

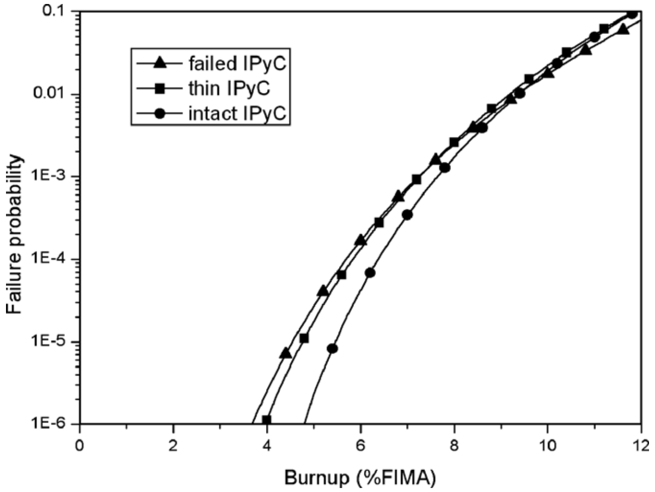

Fig. 14. Failure probability of the SiC with failed, thin and intact IPyC layers.

The variation of tangential stress in failed particles compared with intact particles is given in Fig. 13. Failed particles have higher tangential stress and the stress reversal to tension is observed at lower burnups in failed particles. This results in the observation of higher failure probabilities especially at low burnups in such cases. The difference, however, is not so pronounced at high burnups as presented in Fig. 14.

## 5. Conclusions

Kernel migration is considered a possible failure mode for coated fuel particles. Thermal and mechanical responses of a typical coated fuel particle for HTTR are evaluated in this study for a number of cases representing different operational conditions and physical status of the particle. Results of this study can be summarized as follows:

1. Within the operating temperature and burnup limits, the probability of coated particle failure due to kernel migration is limited. The kernel migration is confined in the buffer layer. On the other hand, pressure vessel failure is more likely due to pressure build-up due to excessive CO formation at high temperatures. Therefore, all the failure cases experienced in this study are due to overpressure.
2. If the extension of kernel migration is significant such that interaction with IPyC and SiC is possible, then, the chemical degradation of coating layers is more likely. This could easily lead failure even at low internal pressures. However, such a case can be observed either at high burnup or with a thin buffer layer.
3. Operating temperature is the key parameter in fuel particle failure. There is no failure expected for the particle with a surface temperature of 1473 K even with kernel migration. This temperature is within the operating temperature limits of the HTTR. However, failure probabilities become appreciable when the surface temperature is 1723 K. This temperature is a typical upper limit for HTTR steady state operation. The extent of kernel migration is significantly affected by the temperature.
4. The effect of kernel migration itself is not so critical on fuel failure. This is justified when temperature and stress values are compared for the same case with and without kernel migration. Pressure vessel failure is the primary mode of failure in high temperature and high burnup conditions. Multiple mode of failures including pressure vessel failure and kernel migration is also probable.
5. CO formation is a critical issue at the high temperature case. As temperature increases, the contribution of CO to the total gas pressure increases. The magnitude of internal gas pressure, and in turn, the maximum stress experienced by the particle also indicate the importance of CO.
6. The integrity of the IPyC layer is also critical in determining the failure probability of the primary pressure boundary, the SiC layer. Early failure of IPyC leads to higher tensile tangential stress at earlier stages of operation.
7. The burnup levels considered here in this study are much higher than the operational discharge burnup for HTTR (about 3.8%). Therefore, failure probabilities quoted in this study are quite high. Although cases represented here are relevant for the HTTR, similar cases may be analyzed for other reactors. However, the kernel and buffer layer dimensions as well as operational parameters such as temperature and temperature gradient, are important for the extent of kernel migration.
8. The accuracy of calculations is mainly limited by the material properties such as pyrocarbon swelling and creep as well as the strength of coating layers employed in this study. These parameters may involve significant amount of uncertainties.
9. The results presented in this study only take the kernel migration and pressure vessel failure modes into account. Failure probabilities for the other failure modes should also be evaluated to correctly predict the coated fuel particle integrity.
10. The analysis reflects only the results for CFPs with a $UO_2$ kernel. A similar analysis may be performed for a CFP with a $PuO_2$ kernel, which operates under higher temperature and higher burnup conditions.
11. The correlation employed in the analysis considers the temperature effect on kernel migration. When the kernel migrates through the coating layers, the same kernel migration rate may not be valid. Density and temperature are primary factors effecting the migration of the kernel through the IPyC layer.
12. Further studies may be useful to assess the effect of kernel migration in IPyC including the effect of SiC degradation.

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