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STRESS ANALYSIS OF COATED PARTICLE FUEL IN THE DEEP-BURN PEBBLE BED REACTOR DESIGN

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ABSTRACT

High fuel temperatures and resulting fuel particle coating stresses can be expected in a Pu and minor actinide fueled Pebble Bed Modular Reactor (400 MW_{th}) design. Such stresses may be different from those expected to arise in 'standard' UO_2-fueled cores. The high discharge burnup aimed for in this Deep-Burn design results in increased power and temperature peaking in the pebble bed near the inner and outer reflectors. Furthermore, the pebble power in a multi-pass in-core pebble recycling scheme is relatively high for pebbles in their first pass through the core. These conditions might result in an increase in the incidence of mechanical failure of the TRISO fuel particle coatings, which serve as the containment of radioactive fission products in the pebble bed design.

The PArticle STress Analysis (PASTA) is used to investigate the integrity of the particle fuel coatings as a function of the irradiation time (i.e. burnup), core position and conditions induced by a Loss Of Forced Cooling (LOFC) incident. For this study, the PASTA code has been coupled to the PEBBED code for neutronics, thermal-hydraulics and depletion analysis of the core. Two deep-burn fuel types, plutonium (Pu) with and without initial minor actinides (MA) content have been investigated with the new code system for normal and transient conditions. The study also incorporates the effect of the statistical variation in the thickness of the coating layers.

Key Words: Deep-Burn, pebble bed, fuel performance

1. INTRODUCTION

The concept of destruction of spent fuel transuranics in a TRISO coated particle fueled gas-cooled reactor is referred to as Deep Burn (DB). The DB concept aims at achieving a fractional burnup of the fuel of the order of 60-70% of fission events per initial metal atom (FIMA). Design and operational constraints in the DB concept include the requirement of achieving this high burnup, using a single pass, multi in-core pebble (re)circulation or cycling scheme. A single pass means that the fuel is used until it reaches its target burnup without being treated chemically or remanufactured between cycling instances through the core.

The reference DB pebble bed concept addressed in this study is based on reactor designs that are substantially similar to the design of the 400 MW_{th} Low Enriched Uranium (LEU) Pebble Bed Modular Reactor (PBMR-400). The goal of the Deep-Burn project [1] is to investigate systematically the ability of the High Temperature Reactor (HTR) to effectively and efficiently destroy Pu and MA, or at least reduce the inventory of these nuclides from legacy used LWR fuel. The DB project considers the HTR in the overall context of the entire fuel cycle and its various

Table I. Deep-Burn Fuel types

Fuel kernel	Fuel loading
Pu fuel	2.6% ^{238}Pu, 54% ^{239}Pu, 24% ^{240}Pu, 13% ^{241}Pu, 6.8% ^{242}Pu
Pu + MA fuel	6.8% ^{237}Np, 2.9% ^{238}Pu, 49% ^{239}Pu, 23% ^{240}Pu, 8.8% ^{241}Pu, 4.9% ^{242}Pu, 2.8% ^{241}Am, 0.02% ^{242m}Am, 1.4% ^{243}Am

alternatives, including the complementary use of various reactor types (fast reactors, LWRs) and of reprocessing and recycling.

The HTR behavior and performance with respect to TRU management and safety is a consequence of the properties of its TRISO coated particle-based fuel. The TRISO coated particles for DB application consist of a 200 $\mu\mathrm{m}$ (diameter) fuel kernel surrounded by two pyrocarbon layers (inner and outer) on either side of a silicon carbide layer. The coated particle is designed to contain the fission products that form within the kernel and that may move to the surrounding buffer layer during irradiation in the reactor core. The design is meant to perform this confinement function both during normal operation up to high burnup levels and during the occurrence of off-normal events. These features contribute to conferring upon the reactor design its 'inherently safe' character.

In a Pu and Minor Actinide (MA) fueled, PBMR-like design, fuel temperatures, temperature gradients, and resulting fuel-particle-coating stresses are expected to be higher than those in TRISO particle of the 'standard' LEU-fueled core. The initial DB-PBR design is undermoderated, but still expected to reach a high discharge burnup. This combination results in larger power and temperature peaking near the inner and outer reflectors in the DB PBR core than in the LEU-fueled case. Furthermore, the fast fluence level reached in the DB fuel is considerably higher than that reached in the LEU case. Finally, as in the LEU case, the pebble power and temperature of a pebble on its first pass through the core in a multi-pass re-circulating scheme are relatively higher than in subsequent passes or in comparison to 'average' pebbles.

The above mentioned effects might result in an increase of the mechanical failure of the coatings, thus potentially adversely affecting the containment of radioactive fission products. The extreme environment in terms of temperature and fluence in the DB core necessitates a thorough investigation of the coated particle performance during both normal reactor operation and off-normal occurrences.

The importance of the coated particle integrity to the safe operation of TRISO based HTRs led to the development of several computer codes for modeling the mechanical and chemical behavior of TRISO fuel under irradiation. Examples are the PANAMA [2] and PARFUME [3] codes. The PArticle STress Analysis (PASTA) code was similarly motivated [4]. It was subsequently adapted for, and applied to, Pu and MA coated particle fuel [5].

More recently the PASTA code was further improved and coupled to the PEBBED code [6] for neutronic, thermal-hydraulic and depletion analysis of the core. This new coupled code system allows for the determination of the coated particle performance as a function of the local and time dependent core parameters (temperature, fluence, burnup, irradiation time and fission product concentration). This allows for determination of the stress effects caused by the power and temperature peaking that are typically found in a DB core design. Furthermore, stresses can be evaluated for slow transients such as a Loss Of Forced Cooling (LOFC) incident.

Two deep-burn fuel types (Pu alone and Pu+MA) (see Table I) have been investigated with the new code system for normal and transient conditions, including the effect of the statistical variation of the thickness of the coating layers. The outline of the rest of this paper is as follows. Section 2 presents the newly developed PEBBED-PASTA code system. Section 3.1 gives a short description of the DB core design and its nominal operating conditions. Results on the reference fuel particle performance at nominal conditions are given in Sec. 3.2. The following sections (3.3 and 3.4) show the stress levels dependence on the radial position within the core and the effect of the variation in the size of the coatings. Also discussed is the influence of the amount of free oxygen released per fission event. In Sec. 3.5 the performance during the LOFC transient conditions is presented. Section 4 concludes on the overall performance of the two types of fuel investigated for the different cases.

2. CODE SYSTEM FOR ANALYSIS OF COATED PARTICLE STRESSES

A schematic overview of the PEBBED-PASTA code system is given in Fig. 1. In this calculation scheme the PEBBED code is used to calculate the environmental parameters of the fuel particles thus providing the boundary conditions for the stress analysis performed with the PASTA code. A short description of the PEBBED and PASTA codes and the calculation procedure used in this work is given in the following subsections.

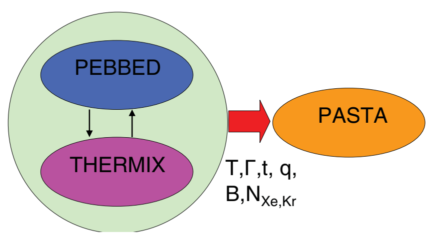


Figure 1. Schematic overview of the PEBBED-PASTA code system for the calculation of coated particle fuel performance.

2.1. PEBBED-PASTA data transfer

The following data are provided by PEBBED and read into PASTA for the analysis for each axial and radial core position and for each pebble core pass (see Fig. 1):

1. T: The temperature of the fuel. PEBBED provides the average fuel, average pebble center and pass-dependent pebble-center fuel temperature histories, which can be used in separate stress analysis evaluations.
2. Γ : The fast neutron fluence (E $>$ 0.1 MeV), which is calculated with PEBBED from a 28 group energy group structure used for the full core calculation.
3. q''': The power density history can be read for use in reconstructing the fuel kernel temperature; the PASTA code can use this information to perform sampling over the temperature profile in the fuel zone of the pebble.
4. B: The burnup level of the fuel.
5. t: The residence time, which is used in conjunction with Eq. (5) for the calculation of free oxygen production.
6. $N_{Xe,Kr}$: The production rate of the stable gaseous fission products of Xe and Kr (^{83}Kr, ^{84}Kr, ^{85}Kr, ^{86}Kr, ^{131}Xe,^{132}Xe, ^{134}Xe, ^{136}Xe) within the kernel.

2.2. PEBBED

The PEBBED code [6] is a tool for analyzing the asymptotic fuel cycle in re-circulating pebble bed reactors. Equations for neutron flux and nuclide distribution in a pebble bed core are solved self-consistently via an iterative scheme. The neutronic solver can use a standard finite difference technique or a nodal diffusion method. The burnup solver uses a semi-analytical method that guarantees convergence and accuracy. Homogenized nuclear data are provided using the SCALE-6 [7] code system, while temperature feedback and thermal-hydraulic analysis is performed with THERMIX(KONVEK) [8].

2.3. PASTA

The PASTA code [4, 5] describes the mechanical behavior of TRISO particles during irradiation and aims at calculating the coating stresses and the corresponding failure probabilities. The TRISO particles have a Pu/MA O_x fuel kernel of 200 μm in diameter at their very center. Adjacent to the kernel is a 90 μm thick porous carbon buffer, which is coated with an inner pyrolytic carbon (IPyC) layer (35 μm), a silicon carbide (SiC) layer (45 μm), and an outer pyrolytic carbon (OPyC) layer (35 μm). These coatings provide the primary containment of the fission products that are generated within the fuel kernel.

PASTA embodies a one-dimensional analytical and multi-layer model that takes into account the visco-elastic behavior of the coating layers and the surrounding graphite during irradiation. The main source of stress in all layers is due to the pressure build-up from the gaseous fission products in the buffer layer resulting in a radial stress on the IPyC. Moreover, the Pyrocarbon (IPyC and OPyC) layers exhibit radiation-induced dimensional changes and creep (in the radial and tangential directions). Finally, the model allows thermal expansion of all layers. PASTA solves the general stress strain equations, which include the aforementioned effects, and are as follows for the radial and tangential direction of a spherical layer [4]:

$$\frac{\partial \varepsilon_r}{\partial t} = \frac{1}{E}\left[\frac{\partial \sigma_r}{\partial t} - 2\mu\frac{\partial \sigma_t}{\partial t}\right] + c\left[\sigma_r - 2\nu\sigma_t\right] + \alpha_r\dot{T} + \dot{S}_r \tag{1}$$

$$\frac{\partial \varepsilon_t}{\partial t} = \frac{1}{E}\left[(1-\mu)\frac{\partial \sigma_t}{\partial t} - \mu\frac{\partial \sigma_r}{\partial t}\right] + c\left[(1-\nu)\sigma_t - \nu\sigma_r\right] + \alpha_t\dot{T} + \dot{S}_t \tag{2}$$

The mechanical failure probability (Ψ) of the coated particle is determined from the magnitude of the (tensile) stress in the SiC layer, which is the main load-bearer, according to the following Weibull distribution:

$$\Psi = 1 - \exp\left(-\ln(2)\left(\frac{\sigma_t}{\sigma_{med}}\right)^m\right) \tag{3}$$

in which σ_t is the tangential (tensile) stress in the SiC layer, σ_{med} the median strength of the of the SiC and m is the Weibull modulus of the SiC strength. These latter two parameters are taken to be σ_{med} = 340 MPa and m = 5, [9]. The internal pressure in the coated particle results from gaseous fission products (Xe and Kr) that accumulate in the kernel and diffuse to the buffer layer during irradiation. The buildup of gaseous fission products can be calculated both analytically and numerically by solving the time-dependent fission product diffusion equation:

$$\frac{\partial C}{\partial t} = \frac{D(T)}{r^2}\left[\frac{\partial}{\partial t}\left(r^2\frac{\partial C}{\partial r}\right)\right] + \beta \tag{4}$$

in which β is the production rate of fission products and $D(T)$ $[s^{-1}m^2]$ is the temperature dependent diffusion coefficient, which can be calculated according to (assuming Xe and Kr as the fission products):

$$D'(T) = 5.10^{-3}e^{(-\frac{Q}{RT})} \tag{5}$$

with $D' = \frac{D}{r^2}$, $Q = 155.4\ 10^3$ J/mol and $R = 8.314$ J/mol/K. In the PASTA code both a numerical method using a finite difference scheme and a fast analytical method [5] for the calculation of the fractional release of fission products from the kernel to the buffer can be used. The source term β is largely determined by production of the gaseous fission products Xe and Kr. Besides direct formation of gaseous fission products, formation of CO gas is possible by a reaction of the free oxygen present in the fuel kernel with the carbon in the buffer layer. The formation of this gas is taken into account by the following empirical formula for oxygen release per fission event (for UO_2 fuel):

$$O/_f = 8.32 \cdot 10^{-11} t_{irr}^2 \cdot e^{(-Z/RT)} \tag{6}$$

It is noted that the expected CO/CO_2 production from DB fuels is higher than for UO_2 fuel [10]. The above equation is used since experimental data for CO production from DB particle fuels is lacking. A sensitivity study is performed assuming more conservative $\frac{O}{f}$ fractions of 0.4 and 0.6 in the following analysis besides Eq. (6).

The resulting pressure (from both fission products and CO accumulation) on the IPyC layer is calculated as a function of the kernel temperature and the buffer volume with the Redlich Kwong equation of state:

$$RT = \left(p + \frac{a}{T^{\frac{1}{2}}V_m\left(V_m + b\right)}\right)\left(V_m - b\right) \tag{7}$$

The ideal gas law is not used here, because it under predicts the pressure significantly.

The PyC coating layers exhibit a dimensional change under irradiation in a fast neutron flux. In Reference [12] the dimensional change as a function of the fast neutron fluence (E >0.18 MeV) is fitted for several temperatures and Bacon Anisotropy Factors (BAFs). Pyrocarbon and graphite materials creep under irradiation, partly reducing the stress. For the pyrocarbon layers a value of $2.0{\cdot}10^{-29}$ (MPa$\cdot$m^{-2})$^{-1}$ for the creep coefficient was adopted from the literature [11]. Thermal expansion of the PyC layers is incorporated in the model and the thermal expansion coefficients, which depend on the BAF, are taken from Reference [12]. Note that for the isotropic case BAF = 1, and α_r= α_t= 50/9= $5.6{\cdot}10^{-6}$ [K^{-1}]. The thermal expansion coefficient of SiC depends on the temperature [9] and has an average value of α_{SiC} = $4.4{\cdot}10^{-6}$ [K^{-1}] in the range $298\ K < T < 1273\ K$. Since the thermal expansion coefficient of the PyC layers is larger than the SiC layer for the entire temperature range, a resulting tensile stress in the SiC layer can be expected for a uniform temperature increase of the coatings.

3. RESULTS

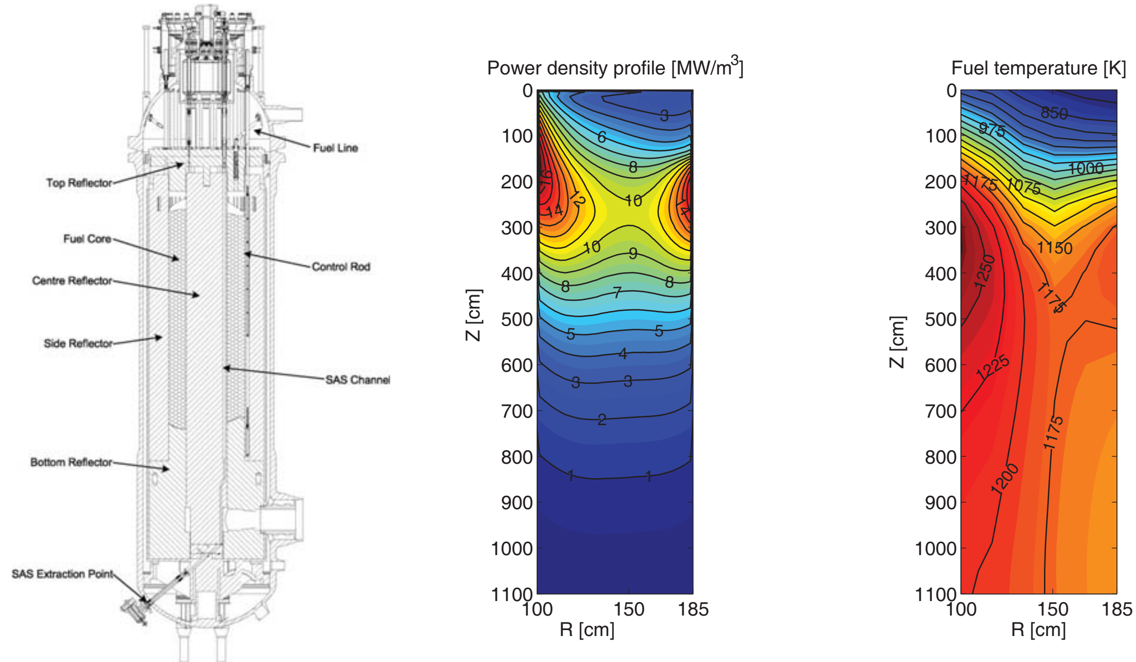
This section presents the results of the fuel performance analysis for the reference particle under nominal conditions first (Sec. 3.1 and 3.2). The following sections illustrate the impact on the performance of the variation in radial core position, CO production, and coating thickness (Sec. 3.3 and 3.4). Finally, LOFC transient conditions are taken into account (Sec. 3.5).

3.1. Deep-Burn pebble bed reactor core and fuel design

The PBMR-400 core design is shown in Fig. 2(a). The 400 MW$_{th}$ pebble bed core has an inner and outer radius of 1 m and 1.85 m, respectively, and is 11 m in height. Table II gives an overview of the fuel and mechanical properties of the coatings used in the PEBBED and PASTA models.

Table II. Material properties of the TRISO coated particles

I/OPyC	Material property	Value
	Young's modulus of elasticity [MPa]	$3.96{\cdot}10^4$
	Poisson's ratio [-]	0.33
	Poisson's ratio of creep [-]	0.4
	Creep coefficient [10^{-25}(MPa.m^{-2})$^{-1}$]	$2.0{\cdot}10^{-4}$
	Dimensional change rate [10^{-25}(MPa.m^{-2})$^{-1}$]	Ref. [12]
	Thermal expansion coefficient [K^{-1}]	Ref. [12]
	BAF	1.0
SiC	Material property	Value
	Young's modulus of elasticity [MPa]	$4.0{\cdot}10^5$
	Poisson's ratio [-]	0.13
	Thermal expansion coefficient [K^{-1}]	Ref. [9]



(a) PBMR core design (b) Power profile (c) T_{fuel} profile

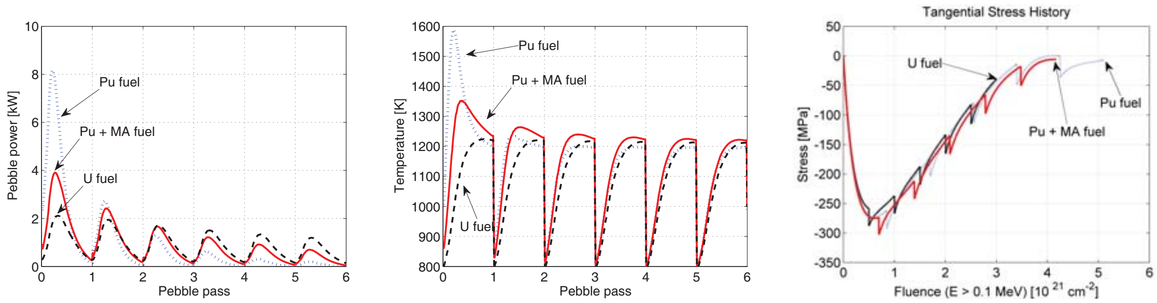
Figure 2. The Deep-Burn PBMR; (a) core design; (b) power profile; (c) fuel temperature profile, showing the temperature and power peaks near the inner and outer reflectors for a Pu fueled core.

3.2. Fuel performance at nominal operating conditions

The power and temperature profiles of the Pu-fueled DB core are shown in Figs. 2(b) and 2(c). Peaks can be seen near the inner and outer reflectors in the top region of the core. These peaks result from a high power level per pebble during the first pebble core pass (out of 6 passes in total), which in turn induces a high fuel temperature for this pass (see Figs. 3(a) and 3(b)).

Results are shown for temperature and power histories for the standard LEU fuel and the two DB fuels (Pu and Pu + MA). These cases correspond to discharge burnup levels of 95, 560 and 680 MWd/kg heavy metal, respectively. From Figs. 3(a) and 3(b) it can be seen that the power and temperature peaking are higher with increased burnup. The resulting stress histories of the SiC layer are shown in Fig. 3(c). The dimensional change (shrinkage) of the IPyC and OPyC layers compresses the SiC layer at the beginning of the irradiation. Then, the increase in the buffer pressure results in a reduction of the compressive stress.

As a result of the higher burnup (residence time) of the DB fuel types, the fast fluence level at the End Of Life (EOL) is considerably higher than that of the LEU fuel. Although the temperature and power at the beginning of the irradiation and the EOL fast fluence level are considerably higher for the DB fuels, the final stress state of the SiC layer remains compressive. Therefore, no significant failure of the average particle is to be expected for these nominal conditions.

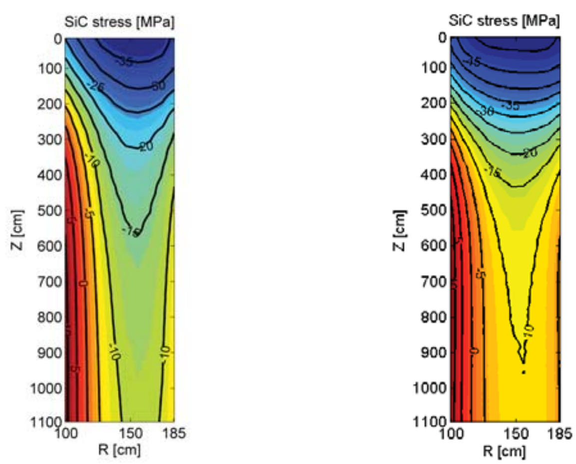


(a) Pebble power (b) Fuel temperature (c) SiC tangential stress

Figure 3. Pebble power (a); fuel temperature (b); and SiC coating stress (c) in Deep-Burn (Pu and Pu+MA fuel) and UO_2 fueled PBMR cores. For all cases the pebbles make 6 (re)circulations through the core.

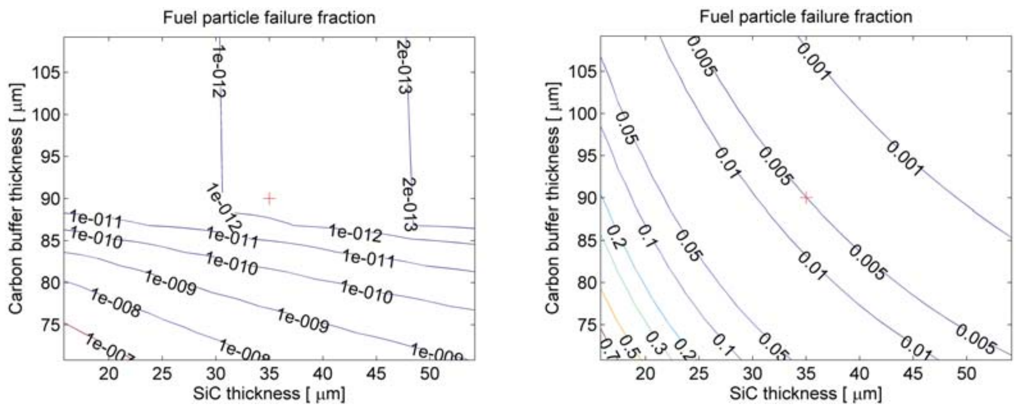
3.3. SiC coating stress as a function of the pebble location

A fuel performance analysis is performed that takes into account the fuel temperature variation in the radial direction of the core. Figs. 4(a) and 4(b) show 2-D core distribution maps of the maximum SiC stress in the particles for the two fuel types. The results show that the pebbles near the radial edges of the pebble bed, which experience high temperatures, contain particles that have a significantly higher SiC stress when compared to the stress in the average particle (see Sec. 3.2).



(a) Pu fuel (b) Pu + MA fuel

Figure 4. SiC coating stress, for a pebble that has been (re)introduced in the core for 6 times, as function of the position the DB core at nominal conditions for Pu (a); and Pu+MA (b) fueled designs.



(a) $\frac{O}{f}$: Eq. (6)

(b) $\frac{O}{f}$: 0.4

Figure 5. SiC failure probability for the Pu-fueled DB core as a function of the buffer and SiC coating thickness assuming Eq. 6 (a) to calculate the free oxygen per fission ($\frac{O}{f}$); (b) and for a fixed value of $\frac{O}{f}$ =0.4. The cross shows the location (failure probability) of the reference particle.

3.4. Effect of variation of the SiC and carbon buffer layer thickness

The coatings and kernel of TRISO coated fuel particles vary slightly in size (thickness) depending of the fabrication process and quality control procedure of the process. A variation from the reference values in coating dimensions has an effect on the particle performance. For example, a reduction of the buffer layer results in less room to accommodate the gaseous fission products, which increases the buffer pressure. This leads to higher stresses in the other coating layers with a higher failure probability as a consequence.

As a result of the nonlinear behavior of the mechanical stresses during irradiation, the stress state (and hence failure probability) of the average (reference dimensions and morphology) coated particle is not necessarily equal to the average stress state of all the various particles (averaged over all dimensional variations). Therefore, the correct prediction of a failure rate should incorporate averaging over all possible dimensional variations weighted by their probability of occurrence. This procedure is described below.

If the distributions $f(x_1), \ldots, f(x_n)$ of (the variation of) the coating thicknesses $x_1, \ldots, x_n$ are known, the consequent expected stress state E can be calculated from the distribution functions and a stress function $\sigma(x_1, \ldots, x_n)$, (see for example [13]):

$$E[\sigma(x_1, \ldots, x_n)] = \int_{a_n}^{b_n} \ldots \int_{a_1}^{b_1} \sigma(x_1, \ldots, x_n) f(x_1) \ldots f(x_n) dx_1 \ldots dx_n \qquad (8)$$

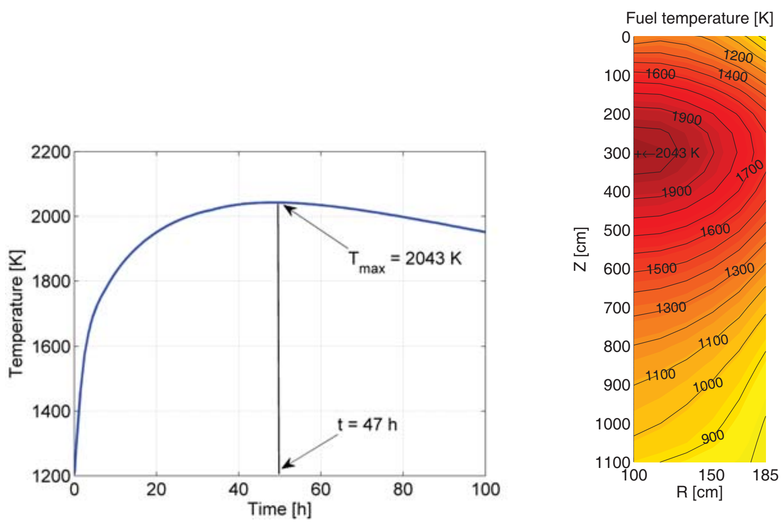
Note that it is assumed that the probability density functions are independent. Similarly, the expected failure probability of all the various particles can be calculated replacing the stress function $\sigma(x_1, \ldots, x_n)$ by the failure probability function $\psi\left(\sigma(x_1, \ldots, x_n)\right)$, which predicts the failure probability as a function of a given stress state. Using this function and rewriting Eq. (8) as a function of discrete points results in:

$$E[\psi(\sigma(x_1,\ldots,x_n))] = \sum_{x_n}\ldots\sum_{x_1}\psi(\sigma(x_1,\ldots,x_n))\,p(x_1)\ldots p(x_n) \tag{9}$$

The above integral is implemented in the PASTA code. The failure probability ($\psi(\sigma(x_1,\ldots,x_n))$) for given particle dimensions is calculated from the coating stresses. This probability is weighted with the probability of the particle having these dimensions ($p(x_1)\ldots p(x_n)$). The expected failure fraction of all the particles combined ($E[\psi(\sigma(x_1,\ldots,x_n))]$), is obtained by evaluation and summation of the failure probabilities of several different cases in which the coating layer thicknesses are varied.

A PASTA calculation has been performed assuming Weibull distributions [13] for the SiC and carbon buffer layer thickness (μ_{SiC}=45μm, σ_{SiC}= 5μm and $\mu_{C_{buf}}$=90μm, $\sigma_{C_{buf}}$= 5μm). The failure probability of the SiC layer as a function of the SiC and carbon buffer thickness has been calculated assuming either Eq. (6) or a more conservative (fixed) value of $\frac{O}{f}$ = 0.4 for the free oxygen production (see Figs. 5(a) and 5(b)).

It can be seen that for ($\frac{O}{f}$: Eq 6) the particle failure probability remains low for all coating dimensions (Fig. 5(a)) with an overall failure probability (see Eq. 8) of $3.8{\cdot}10^{-11}$. However, if a more conservative value of $\frac{O}{f}$ = 0.4 is assumed high failure probabilities can be expected (Fig. 5(b)) with an overall value of $8.0{\cdot}10^{-3}$.



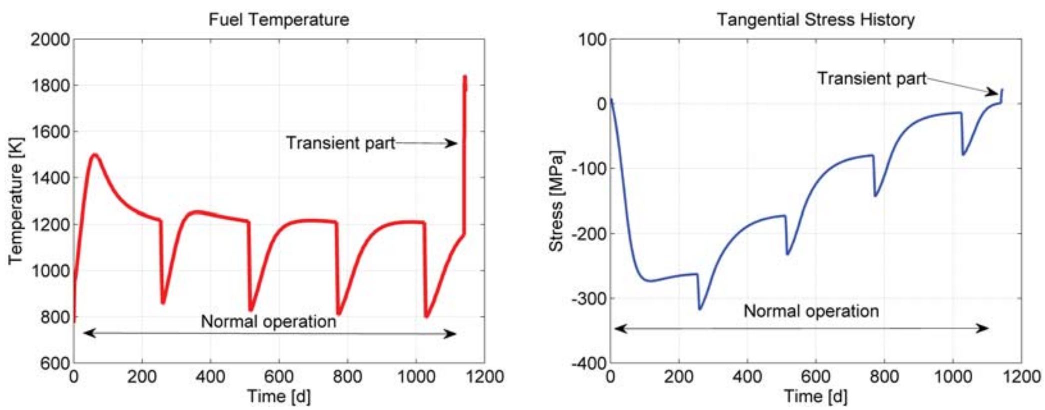
(a) DLOFC maximum fuel temperature history (b) DLOFC fuel temperature profile

Figure 6. Core maximum fuel temperature history (a); and the fuel temperature profile at the time the maximum temperature is attained (b) during a DLOFC transients.

3.5. Fuel performance at Loss Of Forced Cooling conditions

During a LOFC incident the center part of the core can be expected to reach considerably higher temperatures than the nominal operation values. As can be seen from Eq. 7 the pressure in the buffer layer is directly dependent on the temperature. It is also indirectly dependent on the temperature through the diffusion of fission products (Eq. 5) and the CO production rate (Eq. 6). Furthermore, the stress in the SiC layer is a function of the thermal expansion of the SiC layer itself and the PyC layers.

A LOFC transient calculation has been performed using a standalone thermal-hydraulics calculation within PEBBED. Fig. 6(a) shows the core maximum fuel temperature history of a LOFC transient and Fig. 6(b) shows the core temperature profile at the time when the maximum temperature (t = 47 h) is reached.



(a) Fuel temperature history

(b) Sic stress history

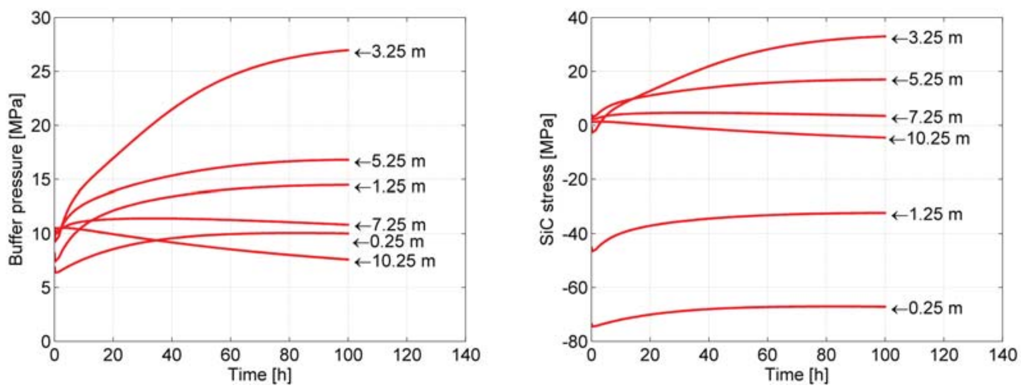
Figure 7. Temperature (a) and stress (b) history for a pebble that has been (re)loaded in the core 5 times and is location in the top region of the core. The increase in temperature during the 100 hour long LOFC transient results in an increase of the SiC stress.

The stress calculation procedure for the transient is as follows:

1. For each point in the lifetime (radiation dose and time) of the coated particle fuel, the stresses in the coatings are calculated assuming normal operation of the reactor. The histories of the fuel temperature, fission product build-up, irradiation time and fast fluence ($E > 0.1$ MeV) during the lifetime of a pebble are generated from the equilibrium core modeled using PEBBED.
2. The fuel temperature history for each position in the core is generated in a DLOFC transient calculation with the THERMIX code. In this transient the temperature difference between pebble surface and pebble center is small as compared to normal reactor operation, since during the DLOFC the heat production is determined by the decay heat only. Therefore, it is assumed that for a given location in the core pebbles with a different burnup class (i.e., representing different points in the lifetime of the pebble) experience the same temperature

history during the transient. This is a plausible assumption since the small difference between pebble center and pebble surface temperature implies that the temperature in all pebbles will be similar.

3. The temperature history of a pebble now consists of two parts. The first part represents normal reactor operation, in which the pebble reaches a given point in life at which the transient occurs. At this point the pebble has passed several times through the core and has reached a certain core position. The second part of the pebble temperature history is determined by the temperature that this core location implies per the discussion above. The temperature history during normal operation and the subsequent transient is shown in Fig. 7(a).
4. For each position in the core the 6 (1 to 6 pebble (re-)circulations completed) possible temperature histories are used to calculate the corresponding histories for the pressure buildup in the buffer layer.
5. The stress state of the coatings is calculated during the entire lifetime of the pebbles (normal operation and subsequent transient). This is shown in Fig. 7(b).



(a) DLOFC pressure history

(b) DLOFC SiC stress history

Figure 8. Pressure (a) and SiC stress (b) history for several axial core positions during a DLOFC transient.

The behavior of the buffer pressure and the resulting SiC during the transient for several axial core positions are shown in Fig. 8. It can be seen that for some positions the buffer pressure and SiC increase significantly during the transient, which in turn increase the failure probabilities of the particles in the respective core regions.

4. CONCLUSIONS

The fuel performance of DB fuel has been investigated using a newly developed PASTA-PEBBED code system for coated particle stress analysis. The predicted failure fractions for the different cases are presented in Table III.

It was found that the average (reference dimensions and average core radial temperature) fuel

Table III. Fuel failure probabilities

Fuel type	Nominal conditions			LOFC transient
	$\frac{O}{f}$: (Eq. 6)	$\frac{O}{f}$ =0.4	$\frac{O}{f}$ =0.6	$\frac{O}{f}$: (Eq. 6)
Pu	$3.8 \cdot 10^{-11}$	$8.0 \cdot 10^{-3}$	$8.0 \cdot 10^{-2}$	$2.6 \cdot 10^{-4}$
Pu + MA	$5.7 \cdot 10^{-16}$	$1.9 \cdot 10^{-3}$	$2.1 \cdot 10^{-2}$	$9.4 \cdot 10^{-7}$

particle performs well. However, if a more conservative value for $\frac{O}{f}$ is assumed significant fuel failure can be expected, especially for the LOFC conditions.

When the performance of the two fuel types are compared it shows from Table III that the fuel without initial MA has significantly higher failure probabilities for all cases. This is the result of the higher burnup achieved in this fuel type, which leads to increased power and temperature peaking.

To reduce the failure probability improved designs for the fuel and/or core are desirable for the Deep-Burn pebble bed reactor. For example, the formation of CO could be reduced by adding an oxygen getters (SiC or ZrC) in the kernel [14]. Furthermore, the power peaking and resulting high temperatures during a LOFC could be reduced by changing core dimensions.

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