Peculiarities of behaviour of Coated Particle fuel in the core of Fast Gas Reactor BGR-1000

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Abstract. Fast Gas Reactor BGR-1000 with thermal power of 2 GW is cooled with high-pressure helium (16 MPa), heated in the core from 350 to 750 ^{o}C. In a steam generator of the power conversion system the thermal power is transferred to the SCW-coolant of secondary circuit, which goes to the turbine with pressure of 30 MPa and temperature of 650 ^{o}C. Reactor core contains Fuel Assemblies (FA) having perforated shrouds. FA's inside cavity among shrouds, control rod guide tubes and central perforated collector is filled with pebble-bed of micro-fuel coated particles (CP). Helium coolant goes into FA through the perforated shroud, passes over CPs removing heat from them and goes then to the FA outlet collector through its perforated wall. The mix-carbide fuel UPuC with mean plutonium content of 16.5% is dispersed in the core in the form of CPs kernels. While loading of heavy atoms is 3640 kg, reactor average burnup amounts 9.7% h.a. Having a breeding ratio of 1.025 reactor can operate in the regime of self-provision of the secondary fuel in the closed fuel cycle. Computational optimization of CP design has given the following performance of the CP kernel and coatings: CP outer diameter of 2030 um, kernel diameter of 1640 um, nondense pyrocarbon buffer coating of 125 um, dense pyrocarbon inner layer (IPyC) of 20 um and outer protective SiC layer of 50 um. In the paper the basic positions of the model of the thermo-mechanics of BGR-1000 coated particles are presented and computational results revealing the effect of CP design on their behavior during irradiation are demonstrated. It is shown, that in the result of the viscous deformation the summarized volume of the kernel and buffer, limited by the elastic SiC, keeps practically invariable. In an equilibrium state the volume changes of the fuel (due to its swelling) and pyrocarbon layers (due to radiation-induced dimension changes) are compensated by changing of the volume fraction of porosity in the fuel and buffer owing to their viscous deformations.

Key Words: High-pressure helium coolant, fast gas reactor, microfuel coated particles.

1. Introduction

One of important factors, forming specifics of usage of Coated Particle microfuel in gas fast breeder reactor BGR-1000 is a big fluence of fast neutrons (2 - 3)x10^{23} n/cm^2, which is a 2 order higher than in reactors HTGRs at the level of burn-up of 15% FIMA. There is a lack of available experimental data on behaviour of coatings of the TRISO-like microfuel in getting so big fast neutron fluence (FNF) at the moment. So, modelling of the core microfuel coated particles behaviour has been conducting given the extrapolation of available mechanical data on pyro-carbon coatings, obtained for FNF less than 10^{22} n/cm^2 [1 – 3], and data on CVD SiC swelling and creep under irradiation up to the damage dose of 100 dpa [4]. Such conceptual studies have been performed for development of a draft design of microfuel Coated Particles of the BGR core and assessment of the reliable operation limits for them.

2. Main requirements to BGR microfuel in getting desirable reactor performance

The experience of the HTGR operation has demonstrated a quite high potential of CP operability and Fission Products' retention inside the boundaries of Coated Particles working under condition of temperatures up to 1100 - 1200^{o}C. This example has encouraged developers of BGR-1000 fast gas reactor to elaborate a reactor design on the base of microfuel particles too. Specifics of the BRG-1000 design is the fast neutron spectrum, high level of FNF and direct heat transfer from the microfuel to the helium coolant flow, surrounding Coated Particles [5, 6]. Accounting these peculiarities, the following requirements has been demanded to design of the core Coated Particles:

- The core with microfuel should provide a five-year fuel campaign with getting high level of the fuel burnup (up to 15% FIMA) providing the quite big volumetric fraction of the fissile materials in the core (not less than 25%);
- Getting an effective fuel consumption (~ 1% FIMA / 1% burnup)
- Ensuring a good workability of Coated Particles up to high level of fast neutron fluence of $3x10^{23}$ n/cm^2 with a probability of CP failure not exceeding 10^{-5};
- Ensuring a high potential of FP retention inside the fuel kernel and CP barriers and non-propagation of heavy metals out of the boundaries of the microfuel particles.

3. Concept design of the BGR microfuel

A concept design of the core microfuel particle and scheme of the Fuel Assembly are shown in Fig. 1. One can see from this picture that microfuel Coated Particles form a pebble-bed placed between two perforated shrouds – outer FA shroud and a shroud of perforated gathering collector. Helium coolant enters to FA through the perforated outer shroud, heats up flowing round CP pebble bed and leaves FA through the perforated shroud of the gathering collector.

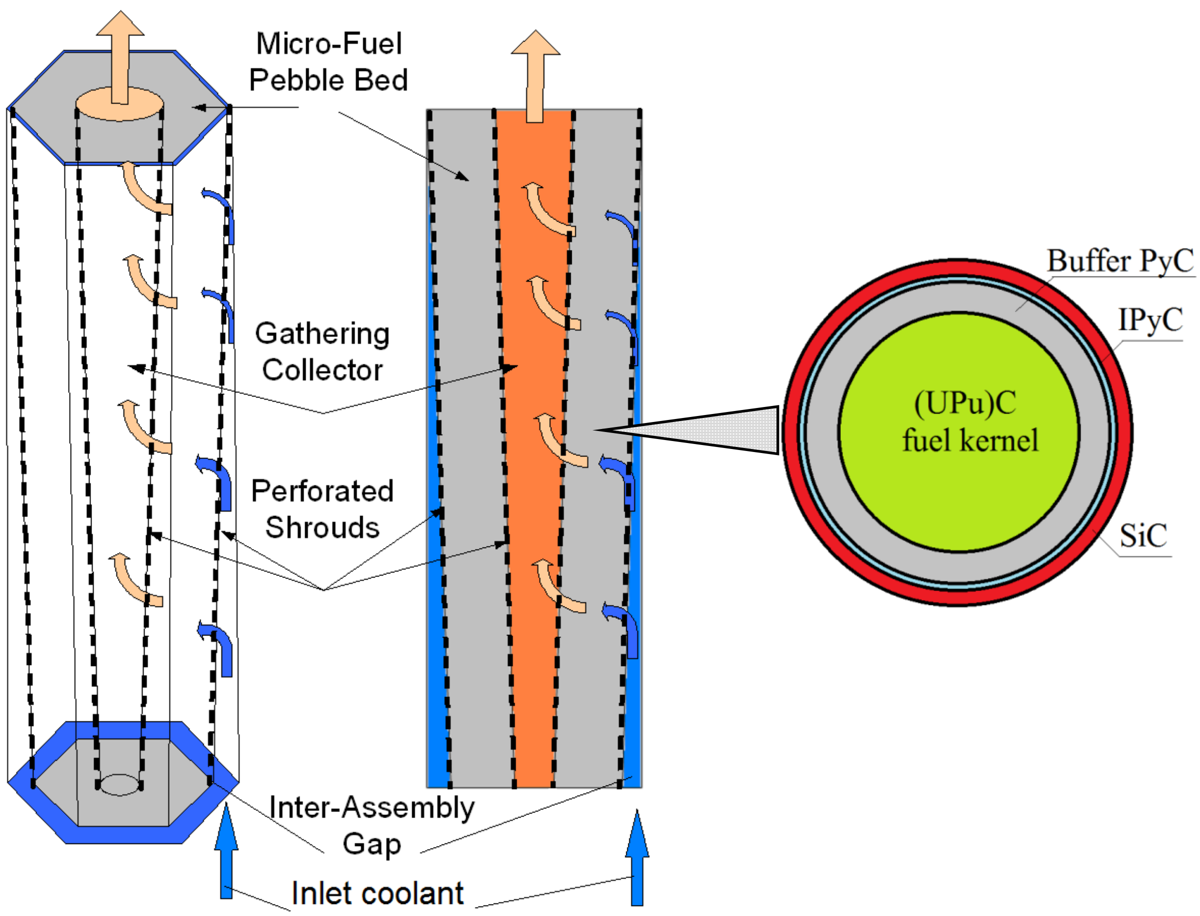

FIG. 1. Scheme of the BGR-1000 Fuel Assembly and microfuel Coated Particle

In draft designing the fuel particle coatings have been chosen to be as thick, as those used in HTGR reactor for effective retention of FPs, whereas a diameter of dense (U-Pu) C fuel kernel has been increased more than three times comparatively to HTGR fuel TRISO particle. Such a choice has been done to get an appropriately big volumetric fraction of the fuel in the core (25%). So, initially a fuel particle has got the following dimensions:

- fuel kernel diameter (um) 1640
- buffer BPyC layer thickness (um) / density (g/cm^3) 80 / 0.8
- dense IPyC layer thickness (um) / density (g/cm^3) 45 / 1.8
- barrier SiC layer thickness, (um) 95

Further optimization of CP design has required a number of factors to be taken into account:

- Dependence of material and mechanical properties on temperature and FNF;
- Quite different behavior of CP kernel and coating layers under irradiation;
- Assignment of appropriate limit of a probability of CP failure.

4. The main aspects of BGR microfuel behavior modeling

The following main phenomena have been taken into account in modeling of microparticle thermomechanics:

- Shrinkage of PyC layers up to FNF of ~ (2 - 3)x10^{21} n/cm^2 (the first 100 h of irradiation) with consequent formation of inner gap between PyC and SiC layers, cracking and fragmentation of PyC.
- Radiation-induced growth of PyC layers after exceeding of FNF over 3x10^{21} n/cm^2;
- Anisotropy of Radiation-induced Dimension Changing (RDC) of PyC;
- Getting the contact of IPyC with SiC approximately at 1.5 % FIMA that corresponds to ~ 3x10^{22} n/cm^2 of FNF;
- Compression of PyC layers by SiC and swelling fuel kernel after getting the contact between PyC and SiC. Taking-up the porosity in the buffer PyC due to its compression;
- Solid-gas swelling of the kernel fuel. Account of specificity of the dense (U-Pu)C fuel kernel growth as incompressible solid body;
- Deformation due to creep of SiC under effect of pressure drop at its thickness and big Fast Neutron Fluence.

The model created for simulating thermomechanics of CP is based on thermo-visco-elastic stress-strain state equations for radial and tangential stresses and strains in approximation of Maxwell body. It takes into account the following sources of deformation:

$$\Phi_i(t) = \int_{t_o}^{t} \left[\alpha \cdot \frac{\partial T}{\partial \tau} + \chi_i(\tau) + \beta(\tau) \cdot \tau + P(\tau) \right] d\tau \quad , \qquad (1)$$

where

$\alpha \cdot \frac{\partial T}{\partial \tau}$ - thermal expansion rate;

$\chi_i(\tau)$ - rate of PyC Radiation-induced Dimension Change in i^{th} direction;

$\beta(\tau)$ - linear rate of fuel swelling;

$P(\tau)$ - linear rate of growth (or shrinkage) of PyC porosity.

For getting a value of the gas pressure under the SiC cover an empirical model taken from [7] for LMFBR experience has been used for estimation of Fission Gas Products (FGP) release from the fuel. This pressure has been set as a boundary condition at the inside of SiC layer up to getting the contact between IPyC and SiC. After onset of the contact the inside pressure acting SiC has been defined from finding the mechanical balance between IPyC and SiC layers as a contact pressure. The coolant pressure has been set as outside boundary condition for SiC.

A model of spherical pores has been applied for taking into account the effect of taking-up the porosity in buffer and inner PyC layers under condition of their compression by swelling fuel and creeping SiC.

The following assumptions have been used in the model:

- Extrapolation of material and mechanical properties of PyC and SiC as well as RDC rates for PyC beyond the FNF > 10^{22} n/cm^2;
- Zerroing the tangential stress in buffer PyC after buffer fragmentation in the result of its shrinkage in the first 100 hours of CP irradiation at the nominal power;
- Tangential tensile stresses unallowable to appear after irradiation-induced growth of buffer fragments, their closure and restoration of whole buffer layer after getting the FNF of $1.3 \cdot 10^{23}$ n/cm^2.
- No other mechanisms of SiC failure are taken into account but overstressing of SiC layer.

5. Computational optimization of the BGR microfuel design

With the use of created model of stress-strain behavior of CP kernel and layers, the series of calculations have been performed in optimization of CP design in meeting the following criteria:

- CP design should provide not exceeding an appropriate preset limit on the probability of CP failure;
- CP design should ensure as maximum volumetric fuel fraction in the core as possible.

Below, some important results of this computational study are presented. As one can see from Fig. 2, relationship between the volume of CP fuel kernel and the volume of buffer PyC layer depends on burn-up and thickness of the SiC barrier layer. Increase of burn-up requires enlarging the buffer. However, the CP buffer layer can be thinner if the SiC barrier is thicker.

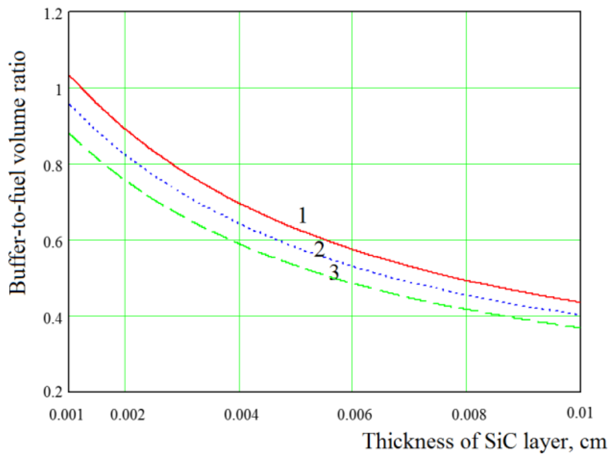

FIG. 2. Dependence of buffer-to-fuel volume ratio on thickness of SiC layer assumed the probability of FE failure equals to 10^{-4}, for three level of the fuel burn-up: 1) – 15% FIMA, 2) – 14% FIMA and 3) - 13% FIMA.

Summarized thickness of all CP layers should be also increased to get higher burn-up (see Fig. 3). Nevertheless, dependence of overall CP coating on thickness of SiC layer has a minimum in the region of 50 – 60 um of SiC, because increase of SiC cannot act as buffer, so quite big low-dense buffer PyC is necessary anyway for compensation of fuel swelling and radiation-induced growth of pyro-carbide.

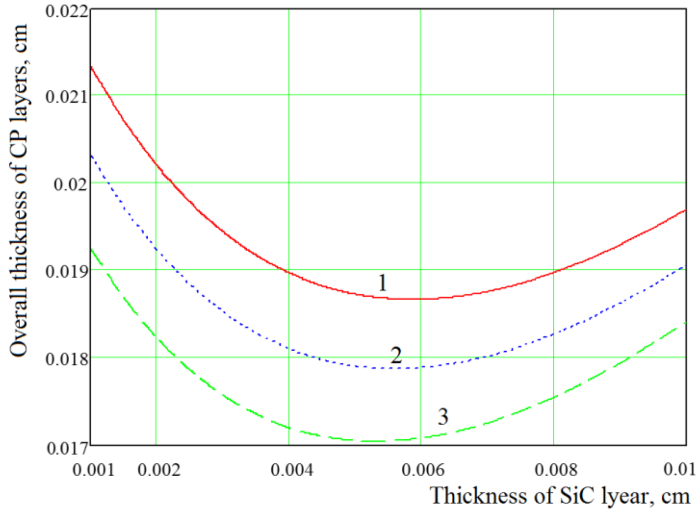

FIG. 3. Dependence of overall thickness of CP layers on thickness of SiC layer assumed the probability of FE failure is 10^{-4} for three level of the fuel burn-up: 1) – 15% FIMA, 2) – 14% FIMA and 3) - 13% FIMA.

An inner gap between PyC and SiC layers (see Fig. 4) is effected by deformations of the fuel and coating layers in course of taking the fast neutron fluence Φ:

$$\Delta(\Phi) = G - \delta(\Phi) - r(\Phi) - u(\Phi)\,, \tag{2}$$

where G - initial value of the gap, $\delta(\Phi)$ - change of the gap due to RDC of PyC layers, $r(\Phi)$ - change of gap due to fuel kernel swelling; $u(\Phi)$ - change of gap due to SiC creep.

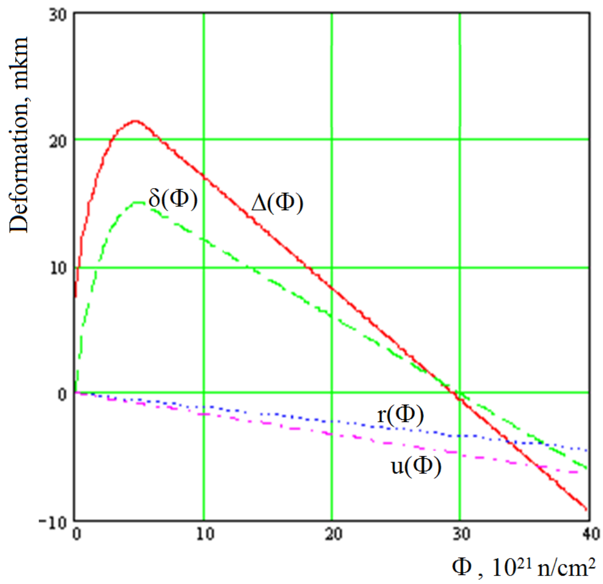

FIG. 4. Dependence of deformations of CP fuel kernel and coatings on fast neutron fluence

As one can see from Fig. 4 the contact between IPyC and SiC is reached at FNF of about $3x10^{22}$ n/cm2. After this moment the value of the contact pressure grows up as it is shown in Fig. 5 and amounts ~ 12 MPa to the burn-up of 15% FIMA.

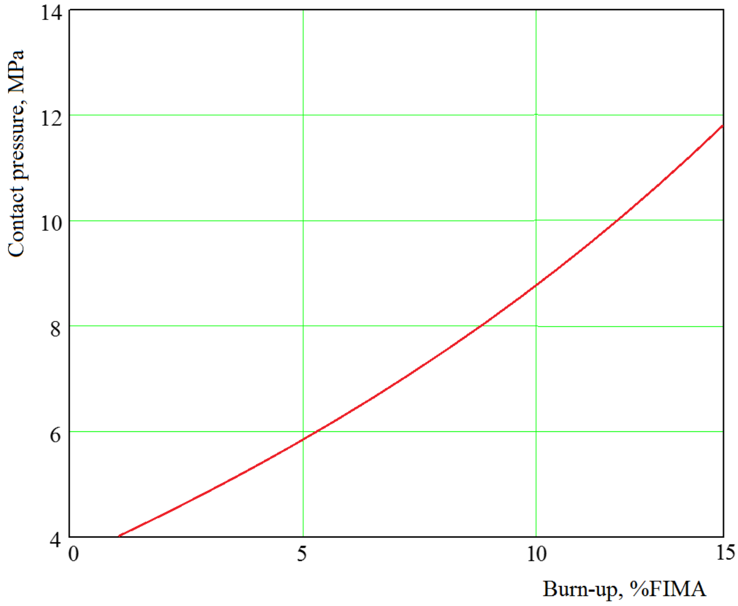

FIG. 5. Dependence of contact (PyC-SiC) pressure on the fuel burn-up for the CP design with the fuel kernel of 1.64 mm, buffer of 125 um, IPyC of 5 um and SiC of 50 um)

After getting the burn-up of 10% FIMA a release of fission products (FP) from the fuel can rapidly increase from 20% to 40%. Given this the inner CP gas pressure (in the volume of the gap plus the volume of the buffer open porosity) jumps up as well (see Fig. 5). Before this moment the contact buffer-to-SiC pressure is a 1.5 time higher than the gas pressure and a creep deformation of SiC layer is controlled by coolant pressure and swelling fuel acting SiC through the buffer PyC. After the gas FP pressure has jumped twice its value becomes higher than contact pressure and the effective pressure acting inner side of SiC rises up as well.

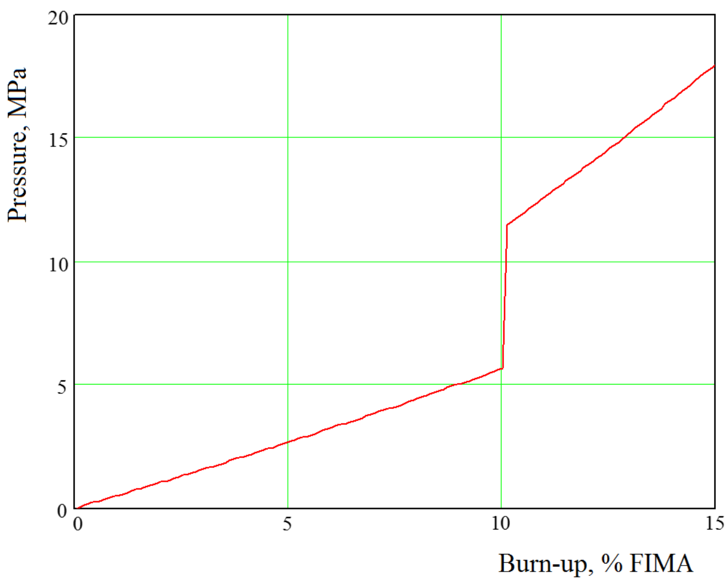

FIG. 5. Dependence of CP inner gas pressure on the fuel burnup (% FIMA) for CP design with the kernel of 1.64 mm, buffer of 125 um, IPyC of 5 um and SiC of 50 um.

Growth of the contact and the inner gas pressures leads to increase of tangential stress in SiC cover coating as it is presented in Fig. 6.

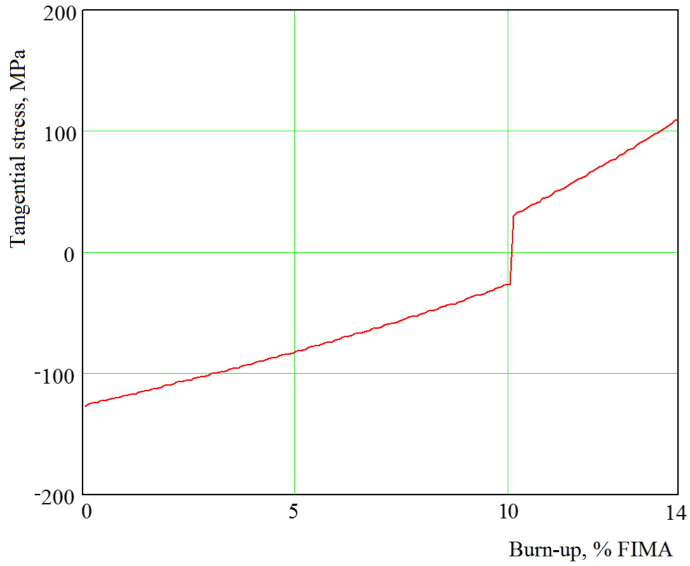

FIG. 6. Dependence of maximum tangential stress in SiC on the fuel burnup for CP design with the kernel of 1.64 mm, buffer of 125 um, IPyC of 5 um and SiC of 50 um

In the created model the strength of SiC material is distributed accordingly with the Weibull low with a median strength value of 350 MPa and a parameter $m = 7$. Given such a distribution low, a probability, that SiC strength is less than 100 MPa, equals to 10^{-4}. One can see in Fig. 6, that tangential stress surpasses 100 MPa at the burn-up of ~ 13.5% FIMA. It means that after this moment the value of probability of SiC to be destroyed exceeds 10^{-4}.

Fig. 6 presents the result for the CP design with overall thickness of CP layers equaled to 180 um. Fig. 7 shows, that to get the burn-up of 15% FIMA CP coatings' thickness should be enlarged up to 190 µm. It can be done, for instance, by increase of IPyC by 10 microns.

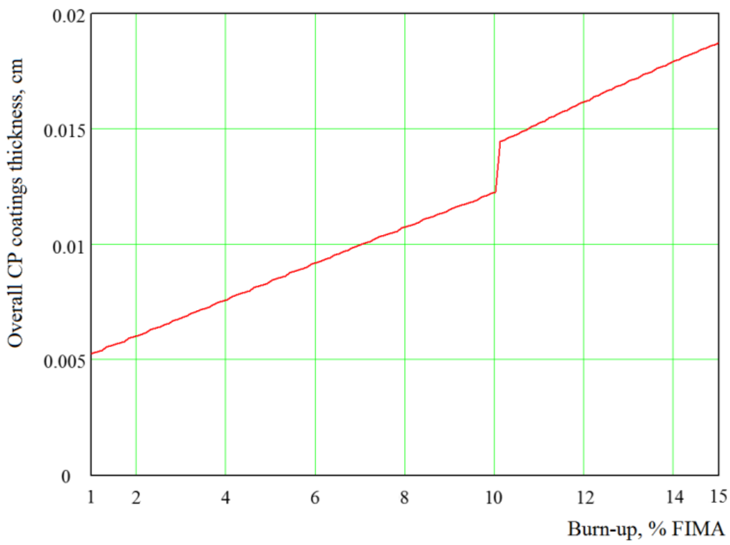

FIG. 7. Dependence of the overall thickness of CP layers on the fuel burnup assumed the probability of CP failure is 10^{-4}

Would we like to enhance a reliability of CP work and decrease the probability of the CP failure by an order, we should to increase the overall CP coatings' thickness by ~ 15 microns (see Fig. 8).

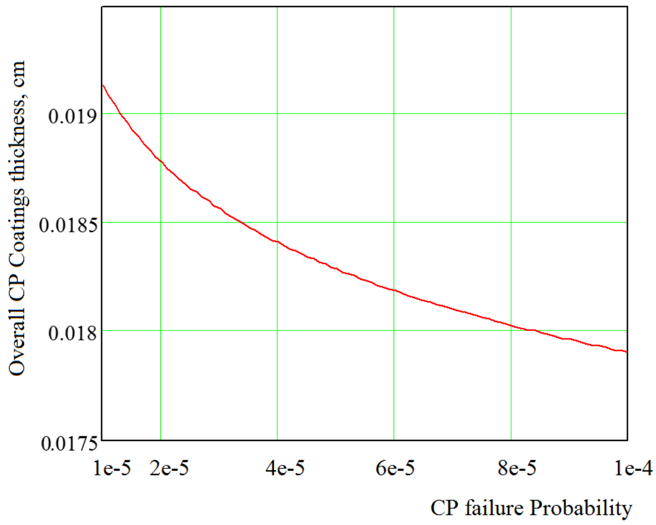

FIG. 8. Dependence of the overall CP coatings thickness on the probability of FE failure at the FIMA=14% (thickness of SiC is 50 μm)

So, in the result of CP design optimization the thickness of the buffer PyC has been increased from 80 to 125 um, because a necessity to compensate the fuel swelling and PyC radiation-induced growth. The value of IPyC layer has been shortened from 45 to 20 um, because IPyC cannot play a part of a buffer on one hand and cannot be a strength barrier as SiC on the other hand. SiC coating has been decreased to 50 um because of this value is an optimum, balancing the overall CP coatings' thickness and appropriate limit on the CP failure probability of 10^{-5}.

6. Conclusion

The model has been created, which simulate mechanical behavior of the BGR-1000 microfuel coated particles with arbitrary combination of PyC and SiC coating layers.

The developed model allows taking into account the deformation due to fuel swelling, SiC creep, radiation-induced dimension changes in PyC and take-up of PyC porosity under condition of compressive deformation of PyC after onset of the contact with SiC.

With the use of created model, a preliminary design of CP has been obtained, which allows to provide big fuel volumetric fraction in reactor core and obtain high burn-up at the level of fuel temperature of 900 ^{o}C with pre-assigned level of CP reliability (probability of SiC failure has set 10^{-5}). The following CP geometries has been obtained after optimization of the CP design: CP diameter of 2.03 mm; the fuel kernel diameter of 1.64 mm, buffer PyC thickness of 125 um, IPyC of 20 um and SiC of 50 um. Initial porosity of the buffer PyC should be of 50 - 60%.

Further modeling and verification needs in the following experimental support:

- Conduction of in-pile tests of microfuel particles in order to research stability of micro-particle fuel kernel and layers' materials as well as potential of FP retention in micro-particles under nominal and accident conditions.
- Conduction of experiments to get the dependences of mechanical properties of CP fuel and layers materials on FNF.

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