Stress Behaviors of a UN TRISO of a 12×12 FCM Fuel Assembly

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1. Introduction

A coated fuel particle (CFP) with a uranium mononitride (UN) kernel has been recently considered as an advanced fuel option, such as in fully ceramic micro-encapsulated (FCM) replacement fuel for pressurized water reactors (PWRs). In FCM fuel, a large number of tri-isotropic coated fuel particles (TRISOs) are embedded in a silicon carbide (SiC) matrix.

The core design of a 12×12 fuel assembly (FA) is an option for the FCM PWR, in which the diameter of a TRISO kernel is 800 μm. The gas pressure produced in a TRISO of the 12×12 FCM FA was estimated throughout 1300 effective full power days (EFPD) [1]. This study treats the quantitative mechanical analysis of a TRISO of 12×12 FCM PWR FA using the gas pressure data and related thermo-mechanical properties of TRISO components.

2. Gas Pressure Buildup in a TRISO

A TRISO in FCM fuel consists of a kernel at its central region and four coating layers surrounding the kernel. The kernel material is UN. The coating layers are a low-density pyrocarbon (PyC), called a buffer, an inner high-density pyrocarbon (IPyC), a SiC, and an outer high-density carbon (OPyC). Table 1 shows the layers of the TRISO used in a 12×12 FCM FA and their thicknesses and densities. The enrichment of the UN kernel is 19.7 atom %.

The gas pressures between 600 and 1000 °C have been calculated using the method described in Ref. [1]. Fig. 1 shows the generated gas species and their pressure evolution at 1000 °C. The major gas species is xenon, and its pressure is about 58 MPa at $15×10^{21}$ n/cm^2 (E_n > 0.18 MeV). The minor species are krypton, helium, and cesium, and their gas pressures are negligible. Fig. 2 shows the variation of the gas pressures in a TRISO according to temperature. At a fluence of $15×10^{21}$ n/cm^2 (E_n > 0.18 MeV), the gas pressures are about 1.7, 14, and 69 MPa at 600, 800, and 1000 °C, respectively.

Table 1 Thicknesses and Densities of Layers in a TRISO

Layers	Thickness, μm	Density, g/cm^3
[a] OPyC	20	1.90
SiC	35	3.18
[b] IPyC	35	1.90
Buffer	50	1.05
UN kernel	[c] 800	14.32

[a] OPyC means outer pyrocarbon.
[b] IPyC means inner pyrocarbon.
[c] This figure means kernel diameter.

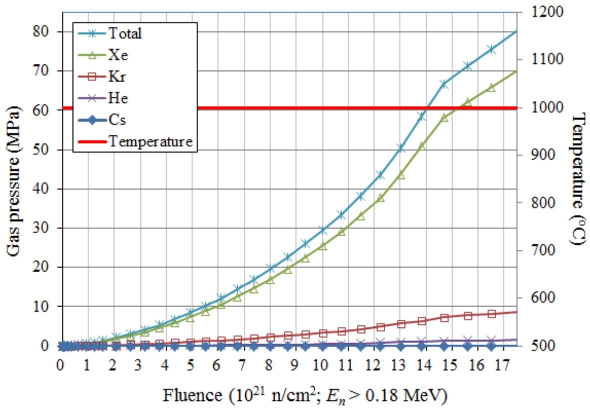

Fig. 1 Variation of Gas Pressure within a TRISO at 1000 °C

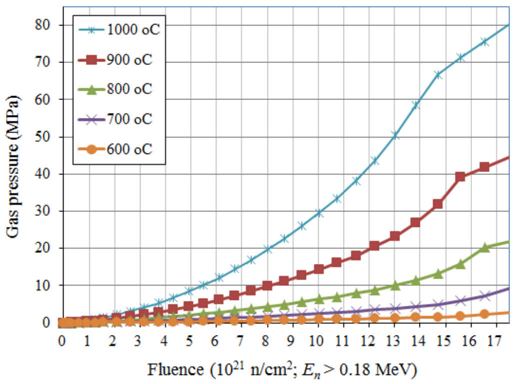

Fig. 2 Variation of Gas Pressure within a TRISO according Temperature

3. Thermo-mechanical Properties of a TRISO

The related thermo-mechanical properties of a TRISO coating layers are given in Ref. [2]. In addition to the gas pressure, the irradiation-induced dimensional change (IIDC) of high-density PyC severely affects the stress state of the coating layers. Fig. 3 shows the IIDCs of high-density PyC, which were calculated using the procedure described in Ref. [3]. Most of them are experimentally known to be below $4×10^{21}$ n/cm^2 (E_n > 0.18 MeV). At above $4×10^{21}$ n/cm^2 (E_n > 0.18 MeV), the IIDCs are simply extrapolated. This must be finely corrected. In Fig. 3, the tangential IIDC means the fractional displacement of the PyC layer. Basically, the PyC shrinks below a certain point of fluence, and then expands above the fluence. Low temperature accelerates the expansion of PyC under irradiation. The PyC shrinkage and expansion cause compressive and tensile stresses on the inner surface of the SiC layer, respectively.

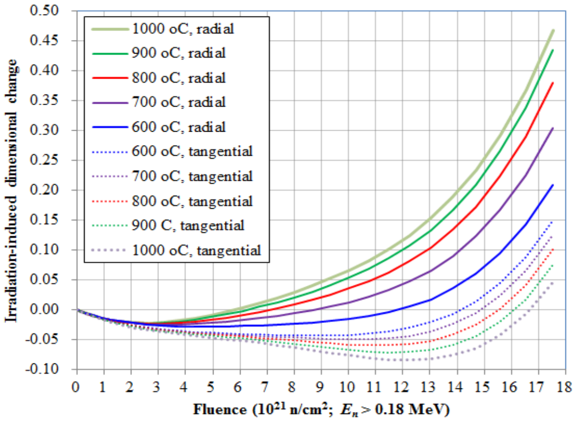

Fig. 3 Variation of Irradiation-induced Dimensional Changes according Temperature

4. Stress Behaviors of a TRISO

Figs. 4 through 6 show the tangential stresses at the inner surfaces of the IPyC, SiC, and OPyC layers during irradiation at 600, 800, and 1000 °C, respectively. At 600 °C, the IPyC layer is likely to break at the early stage of irradiation. The lower the temperature is, the more severe the stress acting on the SiC layer becomes. At 600 and 800 °C, the tangential stresses of the SiC layer are nearly the same in both cases with and without gas pressure applied. This means that the major factor stressing the SiC layer is the IIDC of the IPyC layer. At 1000 °C, however, the tangential stresses of the SiC layer with gas pressure applied are much greater than without gas pressure applied. This means that both the IPyC IIDC and the gas pressure contribute to the development of the stress of the SiC layer. The SiC layer is likely to survive until a fluence of 13×10^{21} n/cm^2 (E_n > 0.18 MeV), which is equivalent to 1100 EFPD.

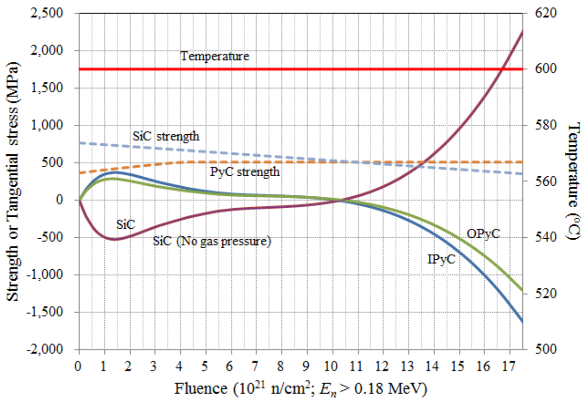

Fig. 4 Tangential Stresses at the Inner Surfaces of Coating Layers at 600 °C

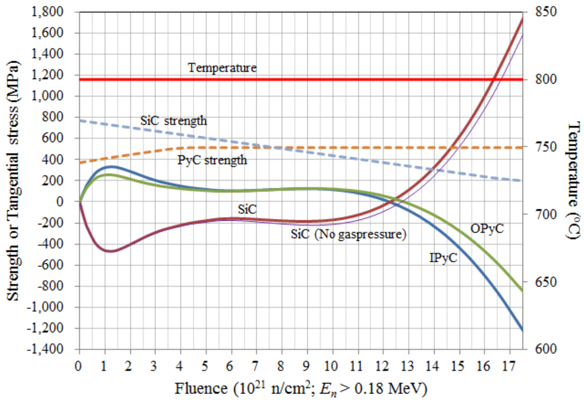

Fig. 5 Tangential Stresses at the Inner Surfaces of Coating Layers at 800 °C

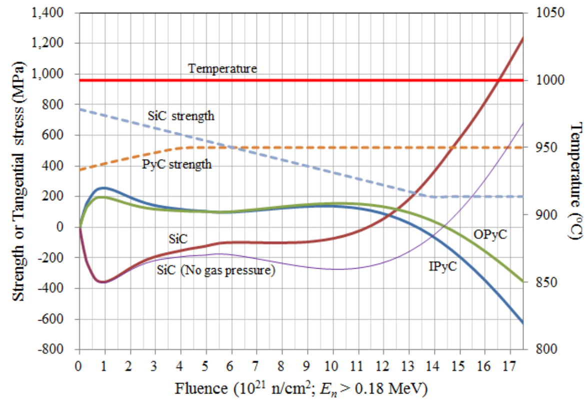

Fig. 6 Tangential Stresses at the Inner Surfaces of Coating Layers at 1000 °C

5. Summary

The stresses of the coating layers in a TRISO with an 800-micrometer diameter UN kernel has been estimated under the normal operation conditions of an FCM PWR. The following conclusions were drawn through this analysis.

- At a high fluence, low temperature accelerates the expansion of IPyC, which gives rise to a severely high tensile hoop stress on the inner surface of the SiC layer.

- At a temperature blow 800 °C, the contribution of the gas pressure to the stress buildup is negligible.
- It is likely that the SiC layer will survive until a fluence of 13×10^{21} n/cm^2 (E_n > 0.18 MeV), which is equivalent to 1100 EFPD.
- The PyC IIDC should be modified into a more realistic form over the extended fluence.

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