Theoretical analysis of TRISO-particle behavior in the Very High Temperature Gas-Cooled Reactor (VHTR)

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1. Introduction

In general, High Temperature Gas-Cooled Reactor (HTGR) is divided into two types. One is a pebble bed system, which contains about 360,000 spherical fuel elements in the case of the HTR-Module that is German gas-cooled reactor. An HTR-Module fuel element consists of approximately 11,000 TRISO coated fissile particles. The other is a prismatic system. Japanese gas-cooled reactor, HTTR, applies this reactor type. The initial core fuel of the HTTR consists of 150 fuel assemblies. An HTTR fuel assembly is so-called a pin-in-block type of hexagonal graphite block containing 31 or 33 fuel rods. A fuel rod consists of a graphite sleeve and of 14 fuel compacts. In a fuel compact about 13,000 TRISO coated fuel particles are dispersed densely.

In this study, we conduct a theoretical analysis of TRISO-particle behavior when they burn in each reactor (HTR-Module and HTTR).

2. Heat transport in a particle fuel

A TRISO coated particle fuel is made up multi-coating layers. The fissile kernel is anchored in the center of the TRISO, and pyrolytic carbon layers and a silicon carbide layer surround the kernel. For these layers, thermal appraisement is carried out.

The steady-state heat transport in the spherical kernel in which heat is generated at a volumetric rate q''' is governed by the heat-conduction equation:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 k\frac{dT}{dr}\right)+q'''=0$$

with boundary conditions $T(R_k)=T_b(R_k)$ and $q''(R_k)=q_b''(R_k)$. Here R_k is the radius of the kernel, T_b is the temperature of buffer layer inside where the kernel and the buffer layer are in contact, and q'' is the heat flux respectively.

In the coating layers, the heat generation is absent in the governing equation. Therefore, the governing equation for the coating layers is expressed as:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2 k\frac{dT}{dr}\right)=0$$

Assuming that total thermal power in each reactor is 600 MW and outlet gas temperature is about 1000℃, two equations are solved. Finally, the temperature profile is obtained as tangible value for several constants is applied to the solution.

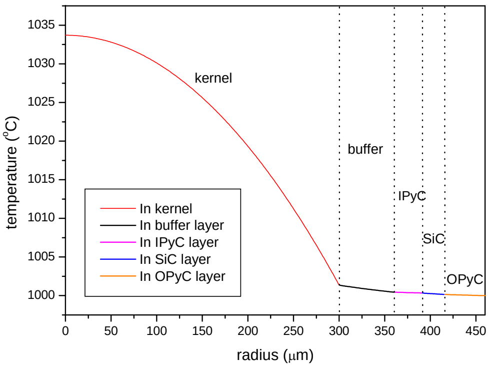

Figure 1. Heat transport in a paricle fuel of HTTR

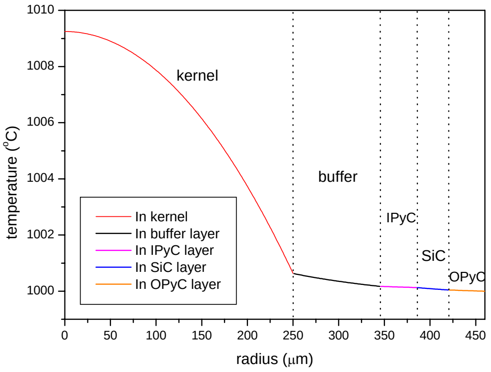

Figure 2. Heat transport in a paricle fuel of HTR-Module

3. Fission product redistribution in a particle fuel

The steady-state fission product redistribution in the spherical kernel in which fission product is generated at a volumetric rate $y\dot{F}$ is governed by the diffusion equation:

$$y\dot{F}+D\frac{1}{r^2}\frac{\partial C}{\partial r}\left(r^2\frac{\partial C}{\partial r}\right)-\lambda C=0$$

with boundary conditions $C_k(R_k)=C_b(R_k)$ and $J_k(R_k)=J_b(R_k)$. Here R_k is the radius of the kernel, C_b is the concentration of buffer layer inside where the kernel and the buffer layer are in contact, and J is the current respectively.

In the coating layers, the fission product generation is absent in the governing equation. Therefore, the governing equation for the coating layers is expressed as:

$$D\frac{1}{r^2}\frac{dC}{dr}\left(r^2\frac{dC}{dr}\right)-\lambda C=0$$

The major fission products that cause the serious accident are known as Pd, Cs and Ag^{110m}. Finally, the concentration profile for these fission products is obtained as the tangible value for the fission yield and several constants is applied to the solution.

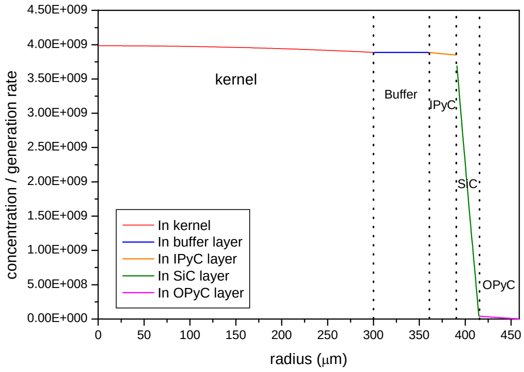

Figure 3. Fission product redistribution in a particle fuel (Cs)

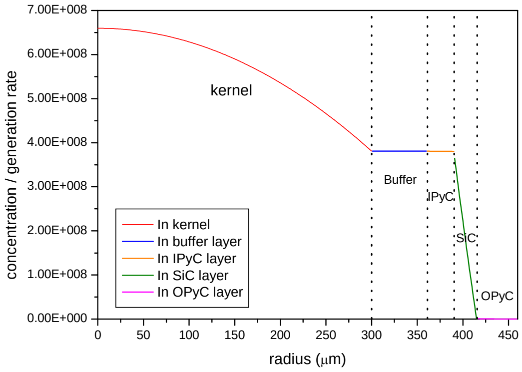

Figure 4. Fission product redistribution in a particle fuel (Ag)

4. Stress build-up in a particle fuel

The steady-state stress build-up in the TRISO-particle fuel is evaluated by the general equations of elasticity. As the general equations of elasticity are arranged, the stress equation is expressed as:

$$r\frac{d^2\sigma_r}{dr^2}+4\frac{d\sigma_r}{dr}+\frac{2E\alpha}{(1-\nu)}\frac{dT}{dr}=0$$

with boundary conditions $\sigma_{r1}(R_1)=-\sigma_{r2}(R_1)$ and $\frac{d\sigma_{r1}}{dr}\Big|_{r=R_1}=-\frac{d\sigma_{r2}}{dr}\Big|_{r=R_1}$. Here σ_r is the radial stress.

Finally, the stress profile is obtained as tangible value for several constants is applied to the solution.

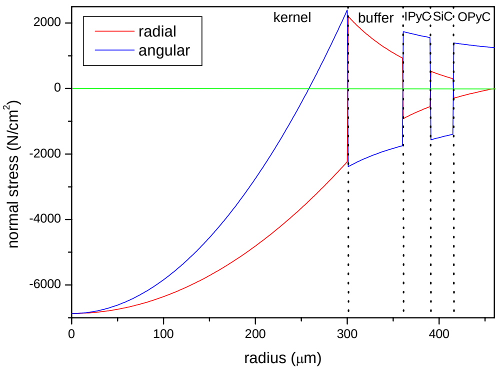

Figure 5. Stress build-up in a particle fuel

5. Discussion

As seen in the consequence of heat transport in a particle fuel, the steep thermal gradient is represented although the radius of particle fuel is very small. Besides, as seen in the results of fission product redistribution and stress build-up in a particle fuel, the fission products are deposited at the silicone carbide layer that acts as pressure vessel. Also, stresses build up at the SiC layer. Consequently, the harsh environment is maintained at the SiC layer while a TRISO-particle fuel burns up.

REFERENCES

[1] Gregory K. Miller and Ralph G. Bennett, Journal of Nuclear Materials 206 (1993)35-49

[2] R. W. Dayton, J. H. Oxley and C. W. Townley, Journal of Nuclear Materials 11, 1 (1964)1-31

[3] IAEA-TECDOC-978, Vienna (1997)

[4] H. Nickel, HTR/ECS 2002 High Temperature Reactor School, Topic3 “Fuel”