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The Effect of the Inner Pressure Induced by Fission Gas on the SiC Layer Integrity

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1. Introduction

Tri-isotropic coated particle (TRISO) is the basic element to form the fuel for the high temperature gas-cooled reactor. TRISO consists of 5 parts; a kernel, a buffer layer, an inner pyrocarbon (IPyC), a silicon carbon (SiC), and an outer pyrocarbon (OPyC) layer. The outer layers act as a pressure vessel to fission safely and keep fission products (FPs) produced in the kernel. Among the outer layers, the SiC layer mainly plays an important role in that it prevents FPs from escaping as a physical barrier. The diffusion coefficient of Cs is, for instance, 100 times bigger in PyC than that of Cs in SiC. Hence, SiC crack means the severe leakage of Cs from TRISO. Since other FPs have the similar trend as Cs does, therefore, the integrity of SiC is important to retain FPs. Here, the mathematical analysis methodol-ogy of the SiC layer fracture will be mainly introduced. Models of the mechanical fracture of TRISO are required to predict stress and limits in a pressure vessel, and determine the failure probability of TRISO.

2. Methods

There are largely two types of SiC fracture mechanism; the one is the mechanical manner which includes the inner gas pressure increase due to fission gases (FGs)/CO, and the irradiation-induced shrink of PyC or swell of SiC. The another is the chemical manner which usually occurs over 1600℃ or in high burn-up. The kernel migration, corrosion and decomposition of SiC correspond to the chemical manner. Assumed that TRISO is burned under the normal operation, however, only the mechanical fracture analysis will be treated here.

Three types of information must be obtained ahead of analyzing the fracture of SiC; the temperature profile, the inner pressure and the stress of TRISO due to irradiation. However, to obtain the inner pressure is carried out here.

2.1 Temperature profile of TRISO

Eq.(1) is the general heat conduction equation in steady state with the boundary conditions.

$$-\nabla\cdot\vec{q}''(\vec{r},T)+q'''(\vec{r},t)=0 \qquad (1)$$

Assume that the volumetric heat generation rate is constant in a kernel region.

$$\frac{1}{r}\frac{d}{dr}(k\cdot r\frac{dT}{dr})+q'''=0 \qquad (2)$$

Note that the thermal conductivity, k, is changed by temperature, burn-up and FPs.

$$k=k_{sol}\cdot k_{pre}\cdot k_{por}\cdot k_{rad}\cdot k_0$$

$k_{sol},k_{pre},k_{por},k_{rad}$ are corresponding to the correc-tion due to FP in solid solution, FP precipitates, porosity and radiation damages, and there are the function of the temperature. [1]

For the outer coating layer, the heat transport is governed by;

$$\frac{1}{r}\frac{d}{dr}(k\cdot r\frac{dT}{dr})=0 \qquad (3)$$

The thermal conductivities of PyC and SiC are also changed.

The temperature profile can be obtained by solving eq.(2) and (3). Figure 1 without using the correction factor is represented to show general the temperature profile of TRISO.

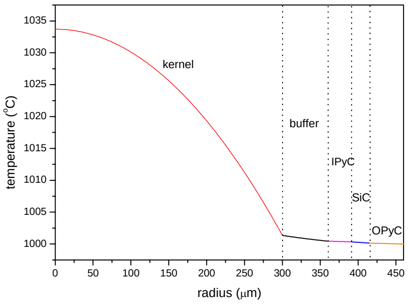

Figure 1. Temperature profile in HTTR (Hyo-cheol Lee, et al, Theoretical analysis of TRISO-particle behavior in the VHTR, KNS)

2.2 Inner pressure

Based on the temperature profile obtained previous, the inner pressure can be predicted though the ideal gas law. Some equations are known as follow;

$$P=\frac{nRT}{V} \qquad (4)$$

, where n is the mole number, which is technically described by K. Sawa et al [2] and Jing Wang et al [4].

However, the fact that the temperature increase makes gas swell, at the same time, and solid expand is known. As the function of temperature, thus, the term should be inserted into eq.(4) to correct the volume decrease by FGs and kernel swelling.

The linear thermal expansion of UO_2 is deduced from experiments as follows [1];

for T<923K:

$$\frac{l_t}{l_{273}}=0.99+9.8\times10^{-6}T-2.7\times10^{-10}T^2+4.4\times10^{-13}T^3$$

for T>923K:

$$\frac{l_t}{l_{273}} = 0.99 + 1.2\times10^{-5}T - 2.4\times10^{-9}T^2 + 1.2\times10^{-12}T^3$$

The amount of the kernel swelling is given by:

$$\Delta V_{\ker} = V_{\ker,0}(\frac{l_t}{l_{273}} - 1)$$

For gas swelling [1],

$$\dot{S}_g = 2.2\times10^{-28}(2800-T)^{11.73}\exp[-0.016(2800-T)]$$

$$V_g = V_{g,0}\dot{S}_g$$

As the porous volume is given by [2]:

$$V_{porous} = (1-\frac{\rho_{buffer}}{\rho_{PyC}})V_{buffer}$$

, where ρ is the density, then the total volume is

$$V = V_{porous} - (\Delta V_{\ker} + V_g) \qquad (5)$$

Through above relationships, the inner pressure, P, can be obtained more exactly.

3. Results and Discussions

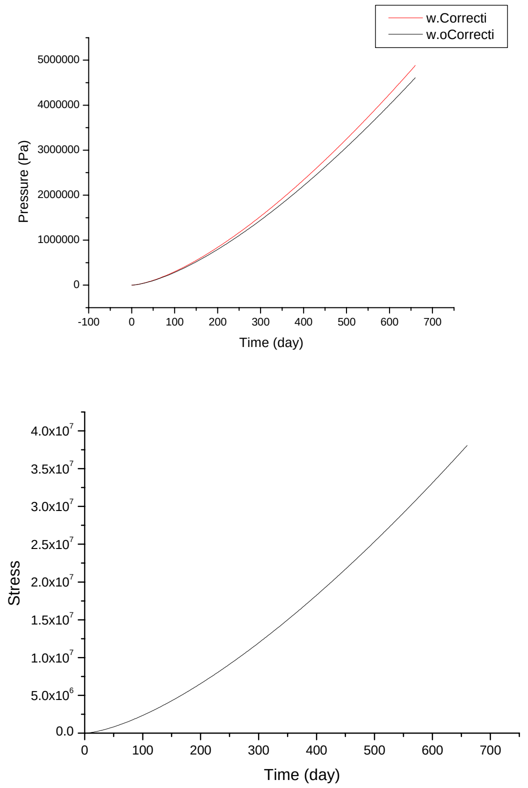

Figure 2. Inner pressure and stress versus time

Figure 2 expresses the trend of the inner pressure with time in the case of the TRISO used in the HTTR. It is assumed that the temperature is constant as 1300℃. Among the correction factors, only the kernel swelling is considered here. As shown below, even the one correction effect cannot be neglected, giving about the 6% larger.

From the results, however, it might seem that the inner gas pressure is not the major factor to occur the SiC layer fracture, if the fact that the ultimate tensile strength (UTS) of SiC is over 350MPa is already known. Then the next to be considered is, thus, the stress effect from irradiation.

There are many equations to explain the stress on SiC. These are only restricted within mainly dealing the neutron fluence. [3] Yet, the stress could be changed with the temperature, which should be treated together with the neutron fluence. For example, the volume of SiC comes to expand and Young's modulus changes with temperature. For them, the empirical expressions are driven in detail. [1] The temperature difference between PyC and SiC also makes the stress on SiC which is described through the thin shell model. [5]

Therefore, to analyze the stress on SiC needs to mainly take into account of temperature and neutron fluence together. The next step is to make the new model to drive the stress distribution due to the neutron irradiation and temperature.

4. Conclusion

It is confirmed that alone the inner gas pressure do not has the strong effect on the SiC fracture and there are some factors not to be ignored for accuracy.

In the last stage, based on the improved methodologies introduced above, the total stress on SiC can be elicited. Comparing the sum of the stress from the inner pressure and the neutron fluence with the UTS, how much impact will be given on the SiC fracture can be analytically obtained, according to the given input variables such as temperature, burn-up, and time.

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