Variation of the Stochastic Strengths of TRISO Coating Layers over Irradiation

Young Min Kim* and Chang Keun Jo
Korea Atomic Energy Research Institute
111, Daedeok-daero 989beon-gil, Yuseong-gu, Daejeon, 34057, Republic of Korea
**Corresponding author: nymkim@kaeri.re.kr*

1. Introduction

A large number of tri-structural isotropic coated fuel particles (TRISOs) are contained in a fuel element of a high temperature gas-cooled reactor (HTGR). A TRISO consists of a fuel kernel in its innermost center and four surrounding coating layers such as a low-density pyrocarbon called buffer, an inner high-density pyrocarbon (IPyC), a silicon carbide (SiC), and an outer high-density pyrocarbon (OPyC) from its inside part.

The integrity of the coating layers should maintain throughout the irradiation in order to prevent the fission product releases. CO, CO_2 and fission gases buildup in the buffer layer of a TRISO. Mechanical stresses develop in the PyC and SiC layers due the pressure in a buffer layer. A coating layer is judged to be broken mechanically if the tangential stress acting on the surface of the coating layer is greater than the ultimate tensile strength (UTS) of the coating layer. The UTS of a coating layer is in a Weibull distribution [1,2].

This study describes the UTS of pyrocarbon and silicon carbide, and how the UTS of a TRISO coating layer changes under irradiation conditions.

2. A stochastic ultimate tensile strength

2.1. Failure probability of a coating layer

The failure probability of a coating layer is given using a cumulative Weibull distribution [3]:

$$P_f = 1 - e^{-\ln 2\cdot\left(S/S_{med}\right)^m} , \quad (1)$$

where S is the tangential stress acting on the inner surface of a coating layer (MPa), S_{med} is the median strength of a coating layer (MPa), and m is the Weibull modulus (dimensionless).

2.2. Weibull modulus and strength of a pyrocarbon

CEGA Corporation [1] suggested the Weibull modulus and strength of an unirradiated pyrocarbon:

$$m_{unirr} = 110.1 - 0.587 \cdot \mathrm{BAF}_0, \quad (2)$$

$$S_{mean,unirr} = \begin{cases} S_0 & , 1.8 \le \rho \le 2.0\,\mathrm{g/cm^3} \\ (1.241\rho - 1.234)S_0 & , 1.1 \le \rho < 1.8\,\mathrm{g/cm^3} \\ (0.644\rho - 0.577)S_0 & , 1.0 < \rho < 1.1\,\mathrm{g/cm^3} \\ 0.0667 S_0 & , \rho = 1.0\,\mathrm{g/cm^3} \end{cases} , \quad (3)$$

where m_{unirr} is the Weibull modulus of an unirradiated pyrocarbon, BAF_0 is the as-manufactured Bacon Anisotropic Factor, ρ is the density (g/cm^3), $S_{mean,unirr}$ is the mean tensile strength of an unirradiated pyrocarbon (MPa), and $S_0(\mathrm{MPa}) = 2918.7 \cdot \mathrm{BAF}_0^2 - 2666 \cdot \mathrm{BAF}_0$.

It is assumed that the Weibull modulus is not a function of fluence and temperature. Based on the assumption of constant strain energy at failure, the change in the strength due to temperature and neutron irradiation is assumed to be related to the corresponding change in elastic modulus in the same direction by [1]:

$$S_{mean,irr} = S_{mean,unirr}\{(1 + 0.23\phi)[1 + 0.00015(T - 20)]\}^{1/2} , \quad (4)$$

where $S_{mean,irr}$ is the mean tensile strength of an irradiated pyrocarbon (MPa), $S_{mean,unirr}$ is the mean tensile strength of an unirradiated pyrocarbon (MPa), ϕ is the fast neutron fluence (10^{25} n/m^2, $E_n > 0.18$ MeV), and T is the temperature (°C). Eq. (4) is assumed to be valid for $1.0 \le \rho \le 2.0$ g/cm^3 and $\phi \le 4\times10^{25}$ n/m^2 ($E_n >$ 0.18 MeV). According to a Weibull distribution, the median tensile strength of an irradiated coating layer is converted from the mean tensile strength of an irradiated coating layer as follows:

$$S_{med,irr} = S_{mean,irr}\,(\ln 2)^{1/m_{irr}}/\Gamma(1 + 1/m_{irr}) . \quad (5)$$

CEGA Corporation [1] recommended that, for a buffer, the flexural strength was 34.5 MPa at the density of 1.0 g/cm^3, and the Weibull modulus was 3.

2.3. Weibull modulus and strength of a silicon carbide

It was recommended that, at room temperature, the Weibull modulus was 6 and the mean strength was 725 MPa. At the elevated temperatures above 1250 °C, the Weibull modulus is 10. For the present, CEGA Corporation [1] assumed that there were no effects of irradiation and temperature on SiC strength.

Allelein et al. [4] used the following correlations to predict their particle failure fraction:

$$S_{med,irr} = max\left[S_{med,unirr}(1 - \phi/\phi_S), 200\right] , \quad (6)$$

$$m_{irr} = max[m_{unirr}(1 - \phi/\phi_m), 2] , \quad (7)$$

where $S_{med,irr}$ is the median tensile strength of an irradiated silicon carbide (MPa), $S_{med,unirr}$ is the median tensile strength of an unirradiated silicon carbide (MPa), ϕ is the fast neutron fluence (10^{25} n/m^2, $E_n > 0.18$ MeV), $\log \phi_S = 0.760 + 650/T$, $\log \phi_m = 0.598 + 650/T$, and T is the temperature (K). CEGA Corporation [1] evaluated that the above relationships had no detailed information or reference on their derivation, and that they did not correlate well with experimental data.

2.4. A Stochastic UTS of a coating layer

The stochastic strength of an irradiated coating layer can be obtained using Eq. (1):

$$S_{irr} = S_{med,irr}\left[-\frac{ln(1-F)}{ln2}\right]^{1/m_{irr}}, \quad (8)$$

where S_{irr} is the stochastic tensile strength of an irradiated coating layer (MPa), $S_{med,irr}$ is the median tensile strength of an irradiated coating layer (MPa), m_{irr} is the Weibull modulus of an irradiated coating layer, and F is a uniform deviate between zero and one, excluding zero and one.

The uniform deviate F can be produced using a random number generator *ran2* which was developed in Ref. [5]. Fig. 1 shows a calculation flow for a stochastic UTS of a coating layer. The uniform deviate F is newly calculated for every particle. The Weibull strength and modulus of an irradiated coating layer are given as a function of unirradiated value, density, and temperature, respectively.

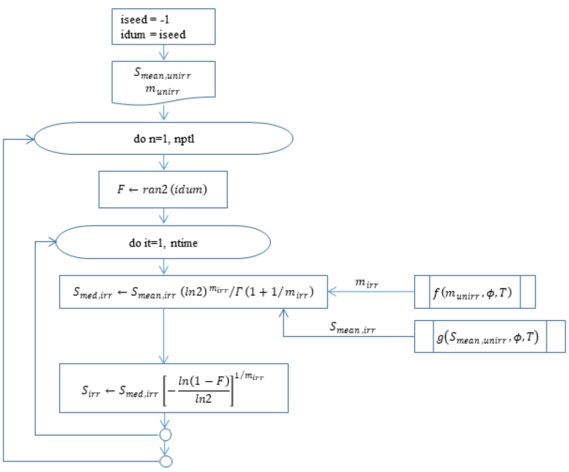

Fig. 1. Calculation flow of a stochastic ultimate tensile strength.

3. Calculation of a stochastic ultimate tensile strength

Table I shows the characteristics of the buffer, IPyC, SiC, and OPyC layers of an unirradiated TRISO for a test calculation. Fig. 2 shows the irradiation fluence and temperature considered in this calculation. Fig. 3 shows the Weibull probability function and cumulative distribution function of the unirradiated pyrocarbon and silicon carbide layers. Fig 4 shows the calculated UTS of the coating layer of five random TRISOs. The five strengths of each coating layer are all different. The strength of pyrocarbon approaches to a maximum value between 900 and 1000 days when the fast fluence becomes 4×10^{25} n/m^2 ($E_n > 0.18$ MeV). That is because the value of Eq. (4) at the fast fluences over 4×10^{25} n/m^2 ($E_n > 0.18$ MeV) was assumed to equal the value of Eq. (4) at the fast fluence of 4×10^{25} n/m^2 ($E_n > 0.18$ MeV). The SiC strengths are constant throughout the irradiation because no effect of irradiation on SiC strength is assumed in this calculation.

Table I: Characteristics of unirradiated TRISO coating layers

	Buffer	IPyC	SiC	OPyC
BAF	-	1.03	1	1.03
Densities (g/cm^3)	1	1.9	3.2	1.9
Weibull modulus	3	9.513	6	9.513
Mean strength (MPa)	34.5	252.7	725.0	252.7
Median strength (MPa)	27.3	230.8	632.7	230.8

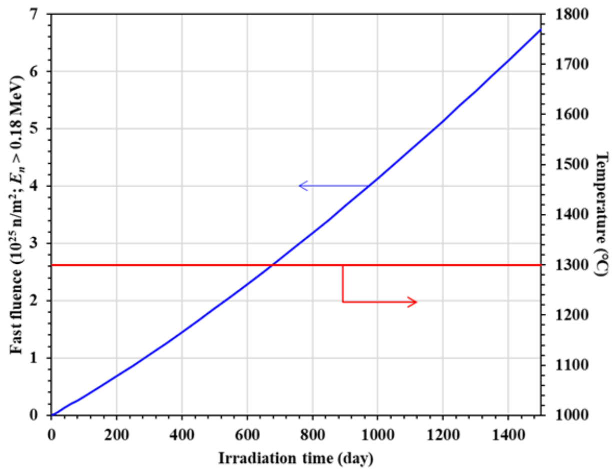

Fig. 2. Variation of fast fluence and temperature.

4. Summary

A calculation flow for the stochastic ultimate tensile strengths of irradiated TRISO coating layers has been set up. The test calculation shows that the five strengths of each coating layer for five random TRISOs are all stochastic. The strength of pyrocarbon approaches to a maximum value near the irradiation point of time when the fast fluence becomes 4×10^{25} n/m^2 ($E_n > 0.18$ MeV). The SiC strengths are constant throughout the irradiation because no effect of irradiation on SiC strength is assumed. For both pyrocarbon and silicon carbide, more sophisticated correlations are needed that explain the effect of irradiation on the strengths beyond the fast fluence of 4×10^{25} n/m^2 ($E_n > 0.18$ MeV).

ACKNOWLEDGEMENTS

This work was supported by the National Research

Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020M2D4A2067322).

REFERENCES

[1] CEGA Corporation, 1993. NP-MHTGR Material Models of Pyrocarbon and Pyrolytic Silicon Carbide. CEGA-002820, Rev. 1, July 1993.

[2] Nemeth, N.N., Mandershield, J.M, Gyekenyesi, J.P., 1989. Ceramics Analysis and Reliability Evaluation of Structures (CARES) User's and Programmer's Manual. NASA Technical Paper 2916, 1989.

[3] Green, A.E. and Bourne, A.J., 1972. Reliability Technology. John Wiley & Sons Ltd.

[4] Allelein, H.J., Bornschein, R., Nabielek, H., Christ, A., Hanson, D.L. 1983. The Behavior of HTR Fuel Under Irradiation. SMiRT 7, Paper No. C519, p. 203. In: SMiRT 7, Chicago, Illinois, 1983.

[5] Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P., 1992. Numerical Recipes in Fortran 77, 2nd ed. The Press Syndicate of the University of Cambridge.

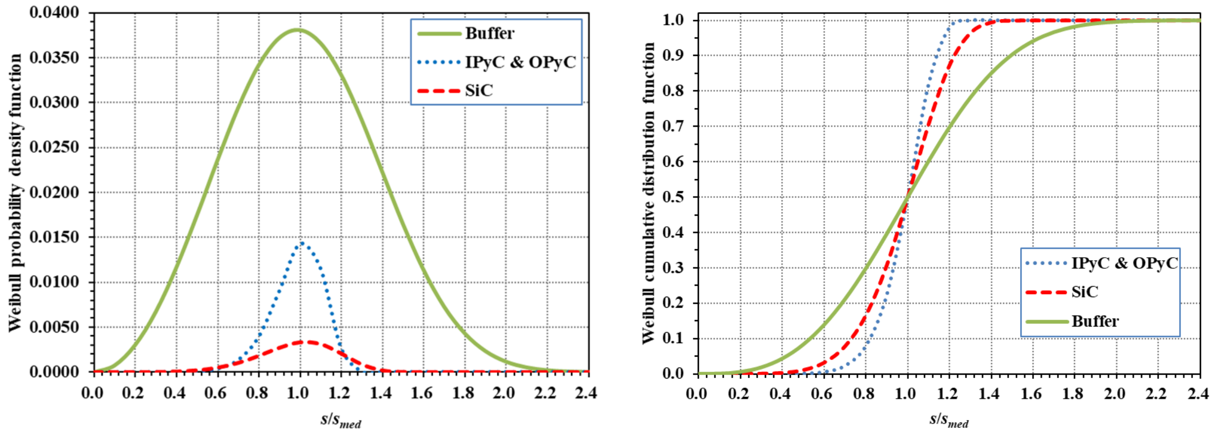

Fig. 3. Weibull probability function and cumulative distribution function of the pyrocarbon and silicon carbide layers.

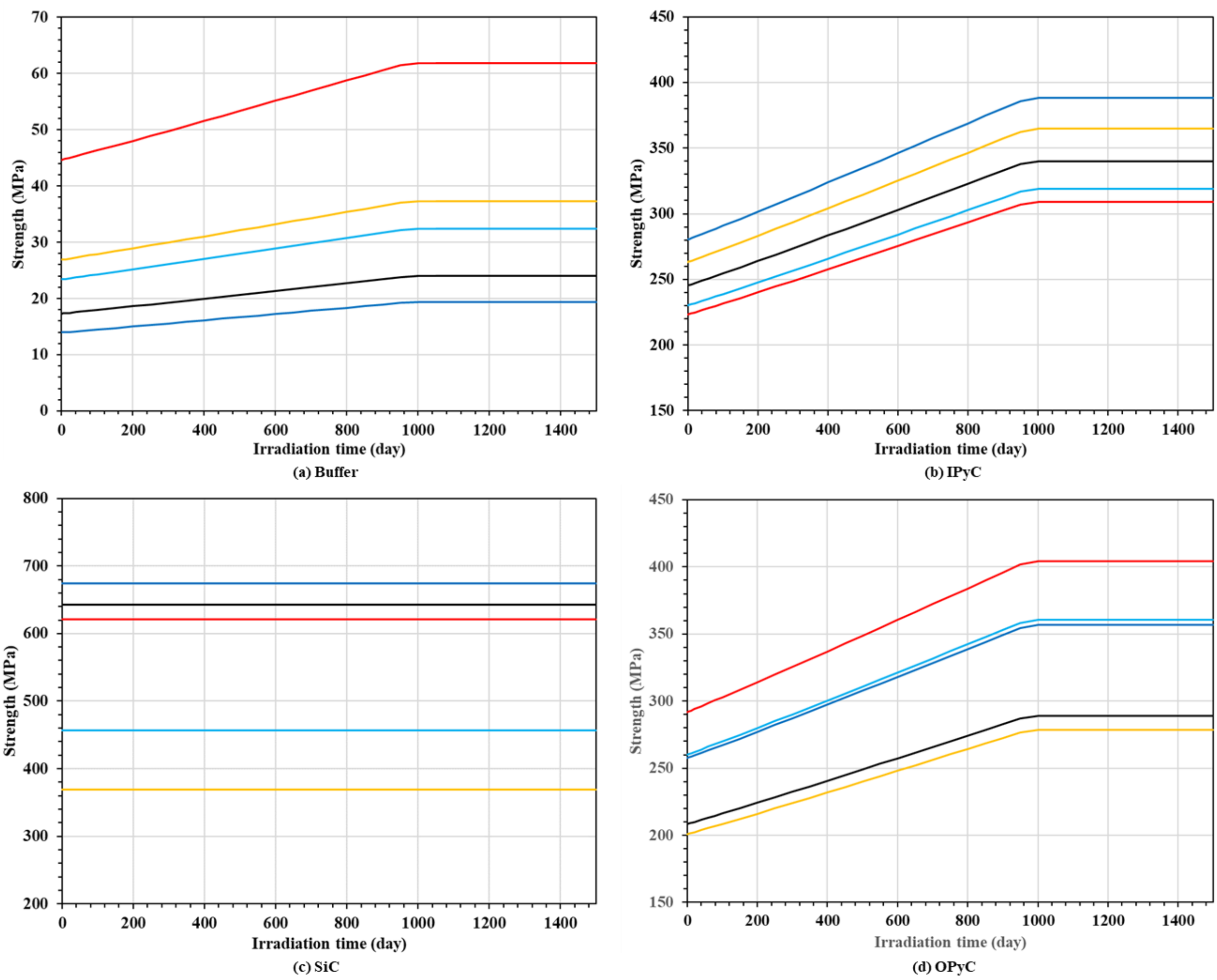

Fig. 4. Stochastic ultimate tensile strengths of the coating layers of five random TRISOs.