Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 27-28, 2016

A Statistical Analysis on the Coating Layer Thicknesses of a TRISO of 350 MW$_{th}$ Block-type HTR

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1. Introduction

A tri-isotropic coated fuel particle (TRISO) is a basic fuel element of a high temperature reactor (HTR). The block-type HTR fuel is a cylindrical graphite compact in which a large number of TRISOs are embedded. There are more than 11 billion TRISOs in a 350 MW$_{th}$ block-type HTR core. Accordingly, it is economically benefit to reduce the TRISO size. On the other hand, the TRISOs should survive the long irradiation in a reactor. Decision of optimal TRISO designs not only reduces the TRISO fabrication cost, but also maintains their integrity.

A TRISO consists of a kernel at its central region and four coating layers surrounding the kernel: buffer, IPyC (inner pyrocarbon), SiC (silicon carbide), and OPyC (outer pyrocarbon), from the inside. One of significant factors deteriorating the TRISO integrity is a tangential stress acting on the inner surface of the SiC layer which results from the gas pressure builds in a buffer, the irradiation-induced dimensional change of IPyC, and the other mechanical properties of the layers.

This study treats a statistical analysis on the optimal layer thicknesses of a UCO TRISO of 350 MW$_{th}$ block-type HTR which cause a minimum tangential stress to act on the SiC layer. Three response surface methods (RSMs) are used as statistical methods and their resulting quadratic models are compared.

2. Statistical Methodologies on a TRISO Design

RSMs offer statistical design of experiment tools that lead to peak process performance [1]. Among various RSMs of the Design-Expert software [2], small- and full-type central composite designs (CCDs) and Box-Behnken design (BBD) were selected as candidate RSMs because they relatively produce a small number of runs. In the CCD, each numeric factor is set to five levels: plus and minus axial points, plus and minus factorial points and the center points [3]. Small-type CCD is recommended when the number of runs must be reduced to the bare minimum. In the BBD, each numeric factor is set to three levels: plus and minus factorial points and the center points [3].

Thicknesses of the three coating layers were selected as numeric factors: 30 ~ 50 μm for the PyC layers and 25 ~ 45 μm for the SiC layer. Tangential stresses acting on the inner surface of the SiC layer were chosen as a response. It was assumed that the kernel diameter was 425 μm, the buffer thickness was 100 μm, the volumetric packing fraction (PF) was 30 %, and the operating temperature was 1200 °C. The ^{235}U enrichment of the UCO kernel is 15.5 weight %. The material properties and design parameters relating to the UCO-TRISO 350 MW$_{th}$ block-type HTR fuel are given in Refs. 4 and 5.

The fuel burnup and nuclide inventory according to the irradiation time was calculated with the McCARD code [6]. The HSC software [7] was used to calculate the thermo-chemical equilibrium. The tangential stresses at the inner surface of the SiC layer were calculated with the COPA code [8]. The statistical analyses were performed with the Design-Expert software [2].

3. Calculation Results

Fig. 1 shows the variation of burnup and fast fluence. The burnup and fluence are about 127 GWd/MTU and 8.1×10^{21} n/cm^2 (E_n > 0.1 MeV) at 1500 effective full power days (EFPDs), respectively. Fig. 2 presents the generated gas species and their pressure evolution at temperature of 1200 °C, when the PF is 30 %. The major gas species is xenon. Cesium gas starts to build up near 1000 EFPD. The total gas pressure is about 17 MPa at 1500 EFPD.

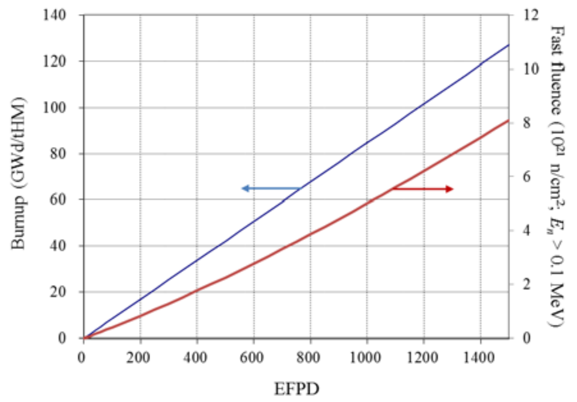

Fig. 1 Variation of Burnup and Fluence

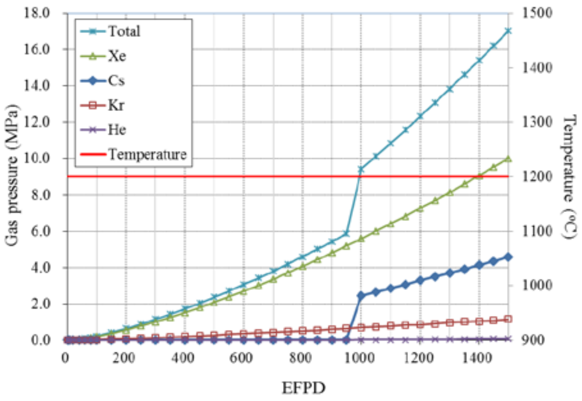

Fig. 2 Variation of Gas Pressure within a TRISO at temperature of 1200 °C and PF of 30 %

Tables 1 to 3 show TRISO design layouts of the full-type CCD, small-type CCD, and BBD, respectively. In the design layouts, replicated runs at a center point are not re-calculated since the COPA code gives same responses. There are 15 runs in the full-type CCD, 11 runs in the small-type CCD, and 13 runs in the BBD, respectively. The CCD may generates a number of decimal places in its factor levels because of its axial points. The decimal places are significant in this statistical analysis, but they do not greatly affect the SiC stress.

Table 1 TRISO Design Layout of Full-type CCD

Run	Thickness, μm			SiC inner tangential stress, MPa
	IPyC	SiC	OPyC	
1	40	35	40	-178.880
2	40	35	56.8179	-226.780
3	40	18.1821	40	-331.070
4	50	25	50	-329.910
5	40	35	40	-178.880
6	40	35	40	-178.880
7	40	35	23.1821	-127.040
8	40	35	40	-178.880
9	30	45	30	-91.892
10	50	45	50	-190.830
11	56.8179	35	40	-233.480
12	30	25	30	-157.520
13	40	51.8179	40	-125.030
14	50	45	30	-143.280
15	23.1821	35	40	-123.140
16	50	25	30	-249.390
17	30	25	50	-237.780
18	30	45	50	-139.360
19	40	35	40	-178.880
20	40	35	40	-178.880

Table 2 TRISO Design Layout of Small-type CCD

Run	Thickness, μm			SiC inner tangential stress, MPa
	IPyC	SiC	OPyC	
1	50	25	50	-329.910
2	50	45	30	-143.280
3	40	35	40	-178.880
4	30	25	30	-157.520
5	54.1421	35	40	-224.970
6	40	49.1421	40	-131.150
7	40	20.8579	40	-290.610
8	40	35	40	-178.880
9	40	35	40	-178.880
10	30	45	50	-139.360
11	40	35	25.8579	-135.550
12	40	35	54.1421	-219.420
13	25.8579	35	40	-131.990
14	40	35	40	-178.880
15	40	35	40	-178.880

Table 3 TRISO Design Layout of BBD

Run	Thickness, μm			SiC inner tangential stress, MPa
	IPyC	SiC	OPyC	
1	40	35	40	-178.880
2	40	45	30	-117.740
3	40	35	40	-178.880
4	30	35	50	-174.620
5	30	45	40	-116.190
6	50	35	50	-240.660
7	30	35	30	-115.390
8	30	25	40	-198.660
9	50	25	40	-290.600
10	40	45	50	-165.250
11	50	35	30	-181.270
12	40	35	40	-178.880
13	40	35	40	-178.880
14	40	25	30	-203.740
15	50	45	40	-167.590
16	40	25	50	-284.140
17	40	35	40	-178.880

Table 4 presents the response surface quadratic models of the full-type CCD, small-type CCD, and BBD, respectively. The quadratic model consists of an intercept, factors, interactions between factors, and second-order factors. Fig. 3 shows calculated and predicted SiC stresses using COPA and RSMs at factorial and center points. The errors in BBD is the smallest among RSMs, even though the differences in the errors of the RSMs are not significant. Fig. 4 displays calculated and predicted SiC stresses using COPA and RSMs at outliers which are exterior points beyond the boundary values of factor levels. The errors in the small-type CCD is the biggest. It is not recommended to apply the quadratic model of the small-type CCD to outliers.

Table 4 Response Surface Quadratic Models

Factors	Full-type CCD	Small-type CCD	BBD
Intercept	-25.61794	123.10089	-5.15094
[a] A	-7.63802	-10.18598	-7.11300
[b] B	9.93355	7.10426	7.97600
[c] C	-7.00316	-9.82059	-6.51850
AB	0.10143	0.12465	0.10135
AC	-4.27500×10^{-4}	0.051801	-4.00000×10^{-4}
BC	0.082202	0.11204	0.082225
A^2	8.07364×10^{-3}	5.79815×10^{-3}	1.76250×10^{-3}
B^2	-0.16778	-0.15620	-0.14556
C^2	0.013023	0.010773	7.18750×10^{-3}

[a] IPyC thickness (μm), [b] SiC thickness (μm), [c] OPyC thickness (μm)

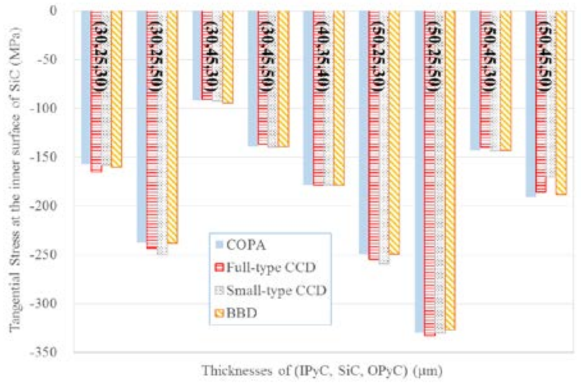

Fig. 3 Calculated and Predicted SiC Stresses using COPA and RSMs at Factorial and Center Points

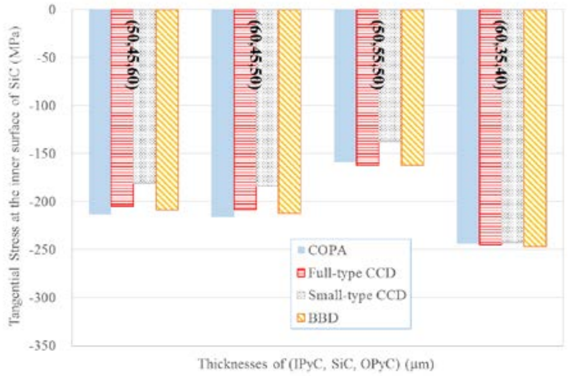

Fig. 4 Calculated and Predicted SiC Stresses using COPA and RSMs at Outliers

Table 5 shows the optimal thicknesses of the coating layers of a TRISO which make both the layer thicknesses and the SiC stresses to be simultaneously minimum. The same target SiC stress range of -500 to 0 MPa was applied to the three RSMs. The optimal thicknesses of IPyC, SiC, and OPyC are 30, 25, and 30 μm, respectively, which are consistent with the results by intuition. Under the current irradiation condition, all the SiC stresses are calculated to be compressive. Then the minimum thicknesses are the optimal ones. For comparison, the optimal layer thicknesses are indicated in parentheses in Table 5 when the target SiC stress ranges were the maximum and minimum values in Tables 1 to 3.

Table 5 Optimal Layer Thicknesses

Layers	Full-type CCD	Small-type CCD	BBD
IPyC	30 [a] (30)	30 (35.3522)	30 (34.0085)
SiC	25 (25)	25 (25)	25 (25)
OPyC	30 (34.7564)	30 (33.8753)	30 (32.153)

[a] The digit in parentheses means an optimal value when the ranges of the SiC stresses were the calculated maximum and minimum values.

4. Summary

Among the RSM quadratic models, the BBD model produces the smallest errors at both interior and exterior points. The errors in the quadratic model of the small-type CCD is the biggest, particularly at exterior points. The CCD has a disadvantage of generating a number of decimal places in its factor levels because of its axial points. It is recommended to use the BBD or the full-type CCD with an adjusted axial point which does not produce the decimal places in its factor levels. More general statistical model for a TRISO design will be secured when the number of factors and responses increases.

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