Failure Behaviors of Quadruple Isotropic Coated Fuel Particles in a Very High Temperature System

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1. Introduction

A tri-isotropic coated fuel particle (TRISO) is a fuel of a conventional high-temperature gas-cooled reactor (HTGR) that is operated at the outlet temperature of 750 °C for about 1000 EFPD. A TRISO consists of a spherical kernel at the center, a low-density pyrocarbon layer called a buffer surrounding the kernel, and three concentric coating layers such as an inner high-density pyrocarbon (IPyC) layer, a silicon carbide (SiC) layer, and an outer high-density pyrocarbon (OPyC) layer.

The SiC coating layer is a main barrier that prevents fission product release out of the particle. The SiC layer is highly prone to be penetrated by fission product attack and thermal decomposition under elevated temperature and extended operation conditions. ZrC has greater chemical and thermal resistance than SiC [1]. Coating ZrC between IPyC and SiC of a TRISO can reduce the failure of the SiC layer by fission product attack and thermal decomposition.

The study treats the failure behaviors of quadruple isotropic coated fuel particles (QUADRISOs) under HTGR conditions. The coating layers of a QUADRISO are IPyC, ZrC, SiC, and OPyC from the inside.

2. Failure behaviors of a batch of QUADRISOs

The kernel of the QUADRISO considered here is UO_2. The kernel diameter is 500 µm. The thicknesses of the buffer, IPyC, ZrC, SiC, OPyC layers are 100, 40, 15, 20, 40 µm, respectively. Table I shows the sixteen failure modes of a QUADRISO.

Table I: Failure modes in a QUADRISO (O: intact, X: failure)

Modes	IPyC	ZrC	SiC	OPyC
0	O	O	O	O
1	O	O	O	X
2	O	O	X	O
3	O	O	X	X
4	O	X	O	O
5	O	X	O	X
6	O	X	X	O
7	O	X	X	X
8	X	O	O	O
9	X	O	O	X
10	X	O	X	O
11	X	O	X	X
12	X	X	O	O
13	X	X	O	X
14	X	X	X	O
15	X	X	X	X

The failure mechanisms considered are pressure vessel failure, fission product attack, and thermal decomposition. Rate of advance of corrosion reaction zone inside a coating layer that reacts with fission products are as follows:

$$\dot{v} = a e^{-\frac{Q}{RT}}, \tag{1}$$

where $\dot{v}$ is the rate of advance of corrosion reaction zone (m/s), a is the pre-exponential factor (m/s), Q is the activation energy (J/mol), R is the gas constant (8.314 J/(mol K)), and T is the temperature (K). Table II shows the pre-exponential factor and activation energy of a corrosion rate equation for SiC and ZrC.

Table II: Pre-exponential Factors and Activation Energies in a Corrosion Rate Equation

Layers	a (m/s)	Q (J/mol)	References
SiC	7.258×10^{-5}	252200	[2]
	5.872×10^{-5}	179500	[3]
ZrC	1.0×10^{-50}	0	[1]

The thermal decomposition rate can be expressed as follows:

$$k(T) = \frac{a}{d_0} e^{-\frac{Q}{RT}}, \tag{2}$$

where $k(T)$ is the thermal decomposition rate (1/s), a is the pre-exponential factor (m/s), d_0 is the initial thickness (m), Q is the activation energy (J/mol), R is the gas constant (8.314 J/(mol K)), and T is the temperature (K). Table III shows the pre-exponential factor and activation energy of a thermal decomposition rate equation for SiC and ZrC.

Table III: Pre-exponential Factors and Activation Energies in a Thermal Decomposition Rate Equation

Layers	a (m/s)	Q (J/mol)	References
SiC	375	556000	[4]
ZrC	1.0×10^{-50}	0	[1]

Fig. 1 shows the evolution of failure fractions of 100 million QUADRISOs in a very high temperature system (VHTS) [5] which are calculated using the COPA code [6]. PyC failure is a main failure mode. No ZrC and/or SiC failure occurred. Fig. 2 shows the evolution of failure fractions of 100 million TRISOs in a VHTS. The

SiC layer starts to be broken at 1100 EFPD. IPyC intact-SiC failure-OPyC intact is the SiC failure mode. No through-coatings failure occurred.

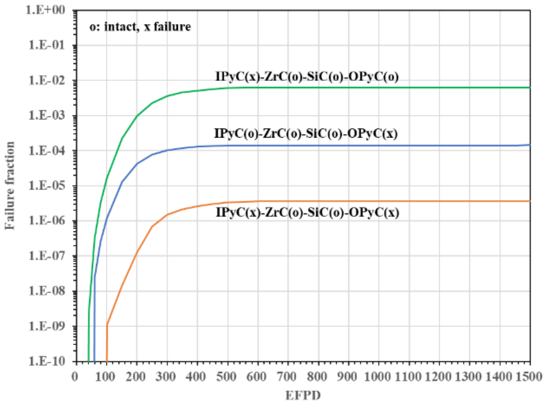

Fig. 1. Failure fractions of QUADRISOs in a VHTS.

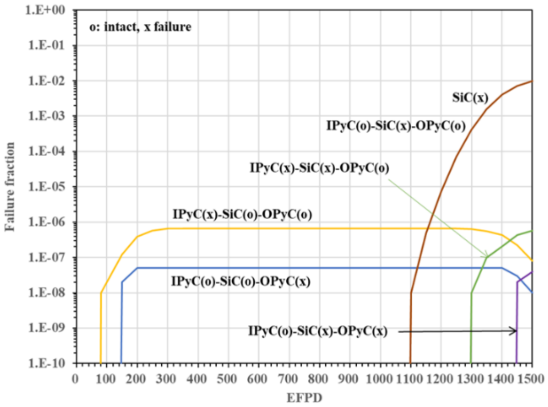

Fig. 2. Failure fractions of TRISOs in a VHTS.

3. Summary

The study analyzed the failure behaviors of a QUADRISO which consists of UO_2 kernel, a buffer, an IPyC, a ZrC, a SiC, and an OPyC. In TRISOs, the SiC failure occurred although through-coatings failure did not occur. In QUADRISOs, no the ZrC and SiC failure occurred. ZrC protects SiC from fission product attack and thermal decomposition. The main failure mode in QUADRISOs is a PyC failure. In elevated temperature and extended reactor operation conditions, the use of ZrC as a coating layer of a coated fuel particle is essential for maintaining the integrity of the particle.

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