

HTR FUEL: SAFETY FEATURES AND PERFORMANCE ANALYSIS

Ü. Çolak⁽¹⁾, B. Yıldırım⁽²⁾, O. Özdere Gülol⁽³⁾

1 Hacettepe University, Department of Nuclear Engineering

2 Hacettepe University, Department of Mechanical Engineering

3 Turkish Atomic Energy Authority, Department of Nuclear Safety

ABSTRACT

High Temperature Reactors (HTRs) are among the candidates for the possible next generation nuclear plant. HTRs are expected to offer inherent safety characteristics, low cost of electricity generation, and short construction period. Especially, the synergy of HTRs with hydrogen generation is a significant advantage. There are two mainstream designs: prismatic and pebble bed. Different fuel options can be considered such as uranium dioxide, uranium carboxide (UCO), and the (U,Pu) mixed oxide. Such reactors can also be used to eliminate weapon plutonium stockpiles and for nuclear waste transmutation. Thorium can be used in such reactors as fuel. Presence of only ceramic materials in the core, large graphite inventory as a heat sink, and inherent safety characteristics of such reactors make them very attractive.

The basic building block of HTR fuel elements is TRISO coated particles. A TRISO particle is made of a fuel kernel, surrounded by a low density porous pyrolytic carbon (the buffer), high density inner pyrolytic carbon, SiC, and high density outer pyrolytic carbon layers. The SiC layer acts as the primary pressure boundary. Normally, SiC is a very strong material and can withstand temperatures up to 1800 C. Beyond that temperature, thermal decomposition may be observed over extended time periods. The buffer layer is used to accommodate volume expansion due to swelling and fission products. Pyrolytic carbon layers protect the SiC layer, keep the SiC under compression, and act as a barrier against gaseous fission products.

In this study, main features provided by TRISO particles, their common failure modes, and basic elements for their performance analysis will be discussed. An important failure mode corresponds to over-pressurization and mechanical failure of the pressure vessel (the SiC layer). Comparisons of mechanical response of the fuel with simple analytical as well as finite element calculations will be provided.

1. INTRODUCTION

High Temperature Reactors (HTRs) are among the candidates for the possible next generation nuclear plant. HTRs are expected to offer inherent safety characteristics, low cost of electricity generation, and short construction period. Especially, the synergy of HTRs with hydrogen generation is a significant advantage. There are two mainstream designs: prismatic and pebble bed. Different fuel options can be considered such as uranium dioxide, uranium carboxide (UCO), and the (U,Pu) mixed oxide. Such reactors can also be used to eliminate weapon plutonium stockpiles and for nuclear waste transmutation. Thorium can be used in such reactors as fuel. Presence of only ceramic materials in the core, large graphite inventory as a heat sink, and inherent safety characteristics of such reactors make them very attractive.

The success of high temperature gas cooled reactors depends upon the safety and quality of the coated fuel particle. In this study, mechanical and probabilistic analysis of a coated fuel particle is modeled by the ANSYS finite element analysis code.

2. COATED FUEL PARTICLE

Coated fuel particle is composed of five layers, which are the fuel kernel, the buffer, inner pyrolytic carbon (IPyC) layer, the silicon carbide layer (SiC) and outer pyrolytic carbon layer (OPyC). Diagrammatic representation of a common coated particle design is shown in Figure 1. Figure 2 presents a micrograph of the same design [1].

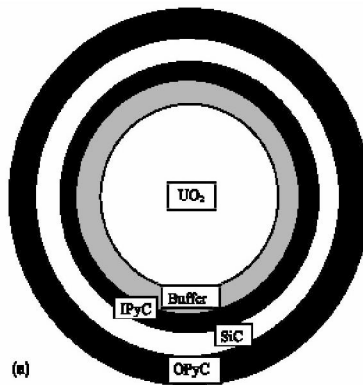


Figure 1 Diagrammatic representation of a coated fuel particle

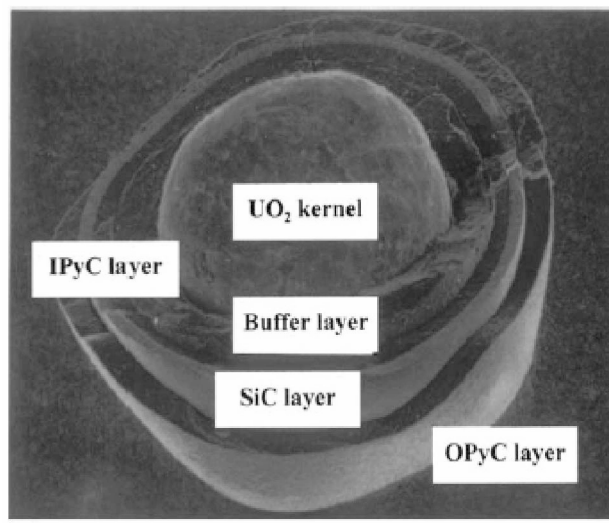


Figure 2 Coated fuel particle micrograph

The kernel contains nuclear fuel, and its composition controls the basic chemistry of the coated fuel particle. Kernel material is commonly UO_2 . Also there exist some other kernel designs of PuO_2 , ThO_2 , UCO , UC_2 and their mixtures. The basic functions of the kernel are controlling particle internal pressure and migration potential by holding down CO production, tying up rare earths as oxides to limit their migration to the coating as well as producing the desired power.

The buffer is a porous layer surrounding the kernel. It is made of low density pyrolytic carbon. The buffer layer captures fission product recoils and protects the IPyC from damage. Also its porous design provides free volume for fission gases and controls the particle pressure. The buffer layer can distort to accommodate kernel swelling [2].

Inner pyrolytic layer is a high density carbon layer deposited on the buffer. It provides a smooth surface for SiC deposition and protects the kernel from the chlorine liberated during SiC composition. The IPyC and OPyC layers provide barriers to the diffusion of fission products out of the particle. They keep the SiC layer in compression during fission so that it can act as a pressure vessel.

The SiC layer is the primary fission product barrier in the coated fuel particle. It provides structural support to accommodate internal gas pressure.

The IPyC and OPyC layers both shrink and creep during irradiation of the particle, while the SiC exhibits only elastic response. A portion of the gas pressure is transmitted through the IPyC layer to the SiC. The pressure

continually increases as the fission continues, thereby contributing to a tensile hoop stress in the SiC layer. Countering the effect of the pressure load is the shrinkage of the IPyC and OPyC during irradiation, which causes them to push or pull inwards on SiC. Due to anisotropy in the pyrocarbon shrinkage behavior, the shrinkage histories differ for the radial and tangential directions. The shrinkage in the radial direction reverses to swelling at moderate fluence levels, whereas shrinkage in the tangential direction continues to high fluence levels [3].

3. COATED FUEL PARTICLE MODEL

Mechanical and probabilistic analysis of a coated fuel particle with UO₂ kernel is performed in this study. Properties of the particle are presented in Table 1.

fuel material	UO ₂
oxygen to uranium ratio	2
enrichment	16.7 %
kernel density	10.5 g / cm ³
kernel diameter	502 μm
coating layer materials	PyC / PyC / SiC / PyC
coating layer thickness	95 / 41 / 35 / 40 μm
density	1.01 / 1.87 / 3.20 / 1.87 (g/cm ³)
PyC modulus of elasticity	3.96*10 ⁴ MPa
PyC Poisson's ratio	0.33
PyC creep coefficient (E>0.18 MeV)	4.93*10 ⁻⁴ MPa
SiC modulus of elasticity	3.7*10 ⁴ MPa
SiC Poisson's ratio	0.13

Table 1. Properties of the coated fuel particle

The coated fuel particle is irradiated for 600 effective full power days. It reached 20 %FIMA end of life burnup and 5.4*10²⁵ n/m² (E>0.18 MeV) fluence at the end of the 600 days period.

Internal pressure due to fission gases Xe, Kr and carbon monoxide is calculated for modeling the layer behavior. Long lived fission products Xe and Kr represent %31 of the total fission products. The gases are assumed to diffuse out of the kernel by equivalent sphere approach. [4,5].

Free oxygen formed due to fissioning of UO₂ is mainly bound by fission products. Excess oxygen diffuses out of the kernel, reacts with the carbon from the buffer layer and forms carbon monoxide. Also there exists carbondioxide of a few percent. CO is the major contributor to the gas pressure inside the layers.

3a. Mechanical analysis

Mechanical analysis of the coated fuel particle is performed by the finite element code ANSYS. The model is composed of two-dimensional representation of the IPyC, SiC and OPyC layers with 1/4 symmetry. Pressure on the IPyC is calculated from Redlich-Kwong gas state law for Xe, Kr and CO. Figure 3 presents the gas pressure inside the IPyC layer. The ambient pressure is assumed to be 0.1 MPa and the average irradiation temperature is 1298 K. The particle is modeled to represent the creep and swelling behavior of the layers. Anisotropy of IPyC and SiC is also taken into account.

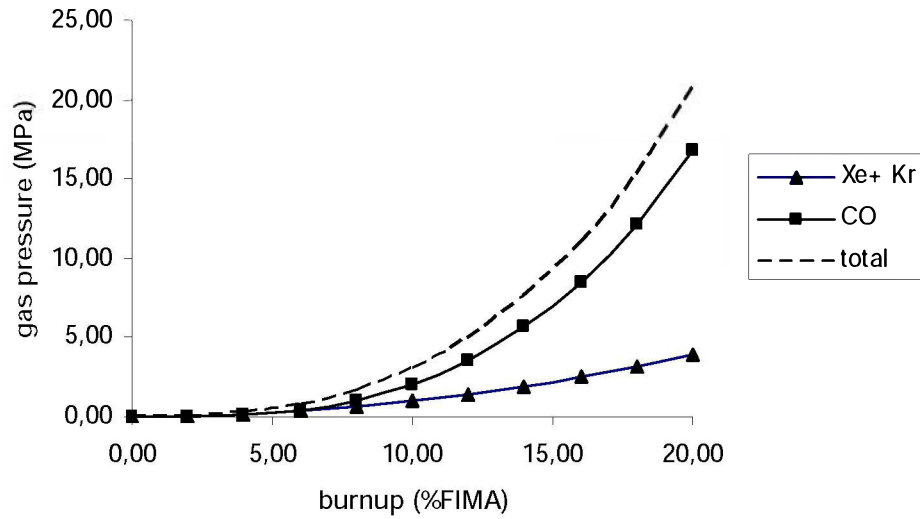


Figure 3. Gas pressure inside the IPyC layer

Stress distributions for the three layers are obtained as a result of the analysis. One of the main failure modes of the coated fuel particle is the pressure vessel failure at stress values above the ultimate tensile strength of the SiC layer. Tangential stress distributions for the three layers with burnup are presented in Figure 4.

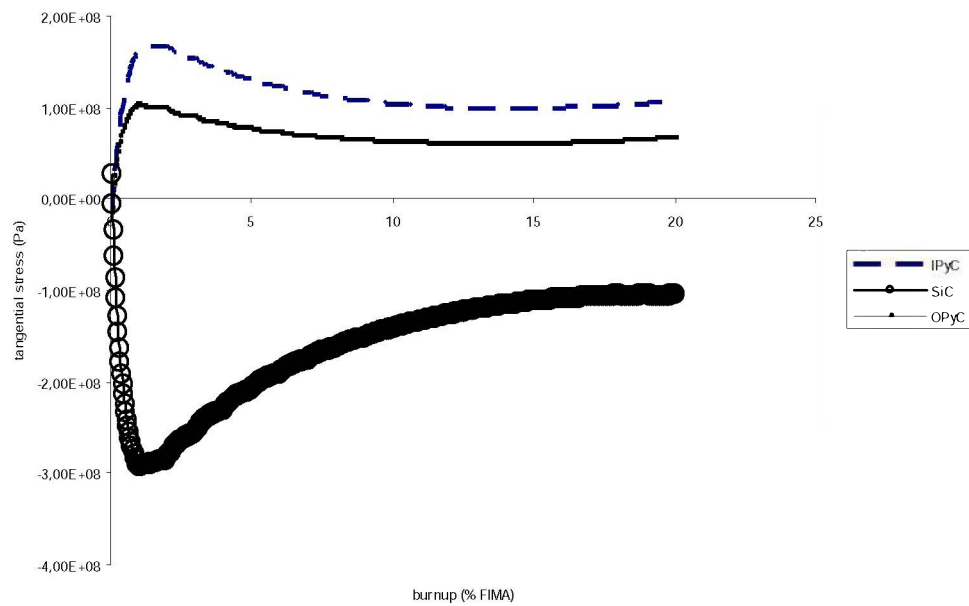


Figure 4. Tangential stress distribution in three layers

The SiC layer is under tension during the entire irradiation period, while the IPyC and OPyC are under compression.

3b. Probabilistic Analysis

Probabilistic analysis calculates failure probability of each coating layer. The mode of failure considered in this study is the pressure vessel failure. This failure probability is described by a Weibull distribution. The failure probability of each layer is calculated by the following equation [6]:

$$f_i(t) = 1 - \exp \left\{ - \ln 2 \times \left(\frac{\sigma_i(t)}{\sigma_{0,i}} \right)^{m_i} \right\}$$

where $f_i(t)$ is the failure probability of layer i at irradiation time t , $\sigma_i(t)$ is the stress on layer i at irradiation time t , m_i is the Weibull modulus for layer i and $\sigma_{0,i}$ is the strength of layer i .

The Weibull modulus and strength of the PyC layers are 5.0 and 200 MPa, respectively. The Weibull modulus and strength of the SiC layer are 8.02 and 873 MPa, respectively.

Failure is explained in two ways in the analysis: SiC failure and through-particle failure. SiC failure considers only the failure probability of the single SiC layer whereas through-coating failure considers the failure probability of the three coating layers. In the analysis, only the tensile stresses are assumed to contribute to the failure of a layer.

Tangential stress distribution in the SiC layer does not have any tensile stress value, so the probability of the SiC failure is equal to zero for the analysis. On the contrary, IPyC and OPyC layers are under tension during the irradiation period. The individual failure probabilities for the IPyC and OPyC layers are calculated as 0.345 and 0.038 respectively. Since the pressure vessel failure probability for SiC is zero, failure of the coated fuel particle due to pressure is not expected for this design and operating conditions.

4. RESULTS

This study includes the mechanical and probabilistic analysis of a typical coated fuel particle with UO_2 . The results of the mechanical analysis represents that SiC layer is under compression during the irradiation. On the contrary, IPyC and OPyC layers are under tension. Stress values for all of the layers are under ultimate tensile strength values. Also probabilistic analysis results show that the particle is not expected to fail due to increase in the gas pressure.

In this study, only pressure vessel failure mode is assumed to have contributed to the failure of particle. There also exist other mechanisms such as kernel migration, asphericity, chemical reaction and debonding that contribute to the failure of a particle. So a full coated fuel particle integrity analysis must include the failure probabilities due to other mechanisms which is the subject of the further studies.

5. REFERENCES

1. D.G.Martin, "Considerations Pertaining to the Achievement of High Burnups in HTR Fuel", Nuclear Engineering and Design, Vol.213, Pages 241-258, 2002.
2. USNRC, "TRISO Coated Particle Fuel Phenomenon Identification and Ranking Tables (PIRTs) for Fission Product Transport Due to Manufacturing, Operations and Accidents", NUREG/CR-6844, Vol.1,
3. G.K.Miller, D.A.Petti, D.J.Varacalle Jr., J.T.Maki, "Statistical Approach and Benchmarking for Modeling of Multi-Dimensional Behavior in TRISO Coated Fuel Particles", Journal of Nuclear Materials, Vol.317, Pages 69-82, 2003.
4. H.Nabielek, K.Verfondern, H.Werner, "Can We Predict Coated Particle Failure? A Conversation on CONVOL, PANAMA and Other Codes", Technical Meeting on Current Status and Future Prospects of Gas Cooled Reactor Fuels held at IAEA, Vienna, 7-9 June 2004.
5. D.R.Olander, "Fundamental Aspects of Nuclear Reactor Fuel Elements", Technical Information Center U.S. Department of Energy, 1976.
6. K.Sawa, S.Ueta, J.Sumita, K.Verfondern, "Prediction of Fuel Performance and Fission Gas Release Behavior During Normal Operation of the High Temperature Engineering Test Reactor by JAERI and FZJ Modeling Approach", Journal of Nuclear Science and Technology, Vol.38, Pages 411-419, 2001.