Annals of Nuclear Energy 119 (2018) 203–213

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Technical note

Influence of accident tolerant fuel cladding material on the European pressurised reactor core neutronic characteristics

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ARTICLE INFO

Article history:
Received 17 October 2017
Received in revised form 29 April 2018
Accepted 2 May 2018
Available online 26 May 2018

Keywords:
Fuel cladding
Nuclear reactor
EPR
Neutronic
Accident tolerant fuel

ABSTRACT

Research on accident tolerant fuel became an important research area to improve safety of the nuclear reactors, especially following the Fukushima disaster. Numerous studies have demonstrated that silicon carbide is a promising candidate material that could potentially replace the zirconium cladding in LWR reactors, which is currently under active research by multiple research and industry organizations. Many of material testing of silicon carbide were already performed and the results are available. Also molybdenum is considered as fuel cladding. This paper is focused on the potential of using silicon carbide and molybdenum as a fuel cladding in the European Pressurized Reactor (EPR) core from the neutronic point of view.

1. Introduction

Materials used for the fuel cladding in light water reactor should be characterized by low thermal neutron absorption cross-section, high thermal conductivity, chemical and mechanical compatibility with the coolant and fuel during normal and abnormal reactor operation, and high melting point. Fuel cladding is a second barrier in a nuclear reactor and first of all, should prevent the penetration of fuel fission products into the cooling circuit.

The rapid increase of interest in accident tolerant fuel is due to the 2011 Tsunami severe accident in Fukushima. One of the factors that can contribute to improving fuel failure resistance is the use of fuel cladding with greater oxidation resistance than zirconium. Multiple materials are considered as cladding for accident tolerant fuel (Cheng, 2012; Cheng et al., 2016; Lee et al., 2017; Kim et al., 2016; Back, 2012; Goldner, 2012; Hinoki et al., 2003; Bhatt et al., 2008; Alkan et al., 2001; Katoh et al., 2007; Li, 2013; Griffith, 2011; Katoh et al., 2006; Lee, 2013; Xu et al., 2015; Brown et al., 2015; Snead et al., 2007; Singh et al., 2018; George et al., 2015; Liu et al., 2017; Brown et al., 2017; Katoh et al., 2014; Silva et al., 2015; Deck et al., 2015; Snead et al., 2005; Kondo et al., 2015; Kulikowska et al., 2010). Ceramics, FeCrAl and molybdenum alloys are examples of the materials which can potentially replace Zr alloys or can be used as a one of the cladding layer. The results presented in (Cheng et al., 2016) proved that coated Mo-alloy cladding can survive in a steam environment at 1200–1500 °C for at least 24 h. However, corrosion resistant of the tubes coated by Mo needs further research. The authors of (Kim et al., 2016) propose surface modification in zirconium cladding by Cr-coated and SiC composite cladding. Research on the SiC cladding for LWRs also take into account various cladding and gap thickness (Singh et al., 2018). Present paper is focused on the SiC and Mo cladding materials.

Comparison of basic parameters of current fuel cladding materials and candidate materials for accident tolerant fuel is shown in Table 1.

Ceramic materials are characterized by high temperature resistance, good thermal conductivity and high creep resistance. Although, silicon carbide (SiC) hardness is a 9.5 in the Mohs scale, at the same time is a very brittle material. Therefore, SiC/SiC composites, consisting of a SiC matrix and reinforced by SiC fiber are proposed as cladding materials. Non-irradiated SiC have very good parameters but during irradiation characteristics of the SiC are changes. Irradiated SiC have even ten times lower thermal conductivity than non-irradiated. Also hardness of the material became lower. One of the biggest advantage of using SiC as a cladding material in light water reactors is swelling. Numerous of publications contain detailed analysis of the irradiation influence on SiC properties (Katoh et al., 2014; Silva et al., 2015; Deck et al., 2015; Snead et al., 2005; Kondo et al., 2015). As it is shown in (Katoh et al., 2014) the biggest value of volume swelling of SiC composites by neutron irradiation occur below temperature 700 K and equal 1–3%. For higher temperatures volume swelling is less around 1% or less. Molybdenum have higher absorption

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https://doi.org/10.1016/j.anucene.2018.05.001
0306-4549/

Table 1
Basic characteristic of fuel cladding materials (Cheng et al., 2016).

Material	Melting point [°C]	Absorption cross section for thermal neutrons [barn]	Thermal conductivity [W/(m·K)]
SiC	~2800	0.019	~20 ÷ 350
Mo	2623	2.6	138
Zr alloy	~1800	~0.19	22
ZrO_2	2715	~0.18	2–3

cross section for thermal neutrons than others materials. However, results of the Mo resistant in steam environment and at high temperature encourage for further research.

Influence of using M5, SiC and Mo cladding on the LWR core is based on the European Pressurized Reactor (EPR) core model. All geometrical models for the neutron calculations correspond to the EPR geometry. The goal of this paper is to analyze influence of new cladding materials on the EPR core without any geometrical changes in fuel elements dimensions or fuel composition. Multiplication factor k_{eff}, reactivity temperature coefficients and power distribution will be investigated in the present paper. M5 is dedicated as cladding in the EPR and results are reference (Kulikowska et al., 2010; Lago and Rahnema, 2016; U.S. EPR Final Safety Analysis Report, 2013).

2. Methods and calculation models

Neutronic calculations were performed using MCNPX code version 2.7.0 developed by Los Alamos and using ENDF/B-VII.1 nuclear data library. MCNPX is 3-dimentonal Monte Carlo code with burnup module. MCNP5/X code allows performing calculation with black, white and reflecting boundary conditions (Hendricks et al., 2008; Schwarz et al., 2008).

2.1. Single fuel model for burnup calculations

To analyze influence of the cladding material on the fuel reactivity, six models of single fuel element were prepared (Fig. 1). Dimensions of these models are shown in Table 2. Burnup calculations were performed using white boundary conditions.

The difference between single fuel models is cladding material. Because of high molybdenum thermal neutron absorption cross section models with different thickness of Mo cladding were prepared. Calculations of the Mo cladding with various thicknesses were performed to choose the best thickness of Mo layer for Mo + M5 model calculations. Enrichment in ^{235}U of the fuel equal 5%. Variants of the calculation models are shown in Table 3. Moderator for the single fuel element model is fresh water (without boron).

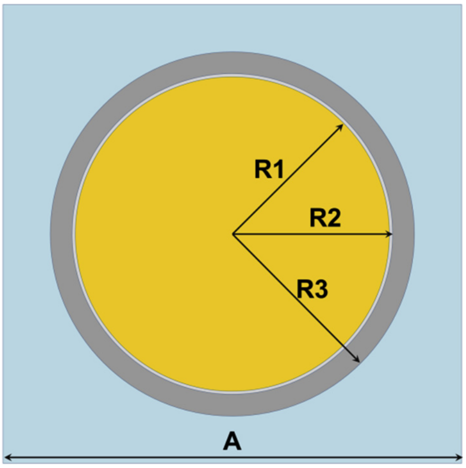


Fig. 1. Single fuel element model.

Table 2
Dimensions of single fuel element model.

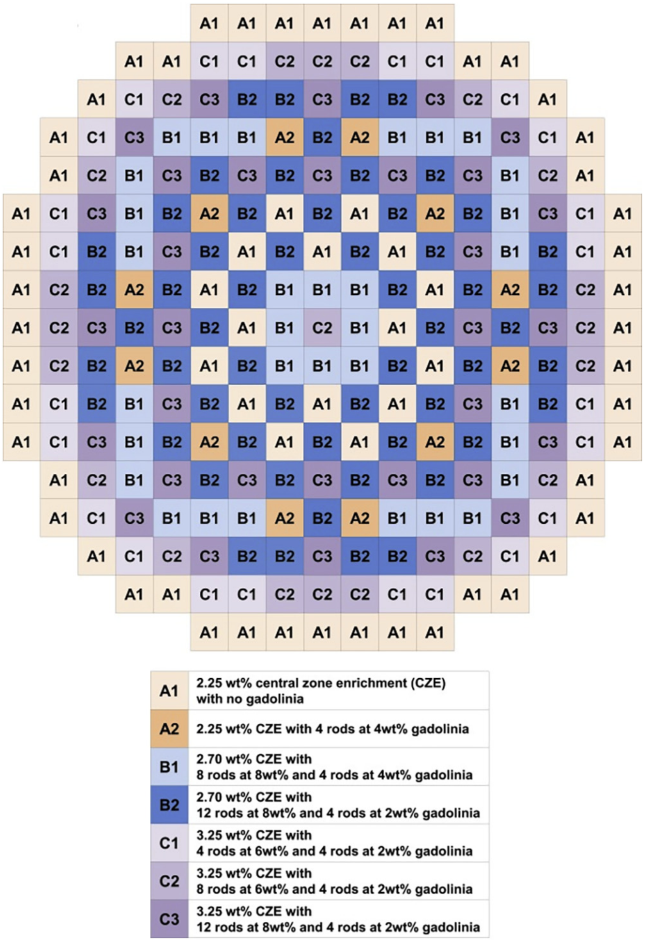
Parameter	Material	Value[cm]
R1	Fuel	0.409
R2	Air	0.417
R3	Cladding	0.474
A	Water	1.260

2.2. The US EPR core model for neutron analysis

To analyze what is the influence of the cladding materials (Mo and SiC) on the reactor core parameters, model of the full EPR core was prepared. Calculations were performed for the EPR core at the Beginning Of Cycle (BOC) without burnup calculations.

Table 3
Variants of the calculation models.

No.	Cladding material	Cladding thickness [cm]	Enrichment in ^{235}U
1	M5	0.057	5 [%]
2	SiC		
3	Mo		
4		0.020	
5		0.010	
6	Mo + M5	0.010 + 0.047	



					A1	A1	A1	A1	A1	A1	A1					
			A1	A1	C1	C1	C2	C2	C2	C1	C1	A1	A1			
		A1	C1	C2	C3	B2	B2	C3	B2	B2	C3	C2	C1	A1		
	A1	C1	C3	B1	B1	B1	A2	B2	A2	B1	B1	B1	C3	C1	A1	
	A1	C2	B1	C3	B2	C3	B2	C3	B2	C3	B2	C3	B1	C2	A1	
A1	C1	C3	B1	B2	A2	B2	A1	B2	A1	B2	A2	B2	B1	C3	C1	A1
A1	C1	B2	B1	C3	B2	A1	B2	A1	B2	A1	B2	C3	B1	B2	C1	A1
A1	C2	B2	A2	B2	A1	B2	B1	B1	B1	B2	A1	B2	A2	B2	C2	A1
A1	C2	C3	B2	C3	B2	A1	B1	C2	B1	A1	B2	C3	B2	C3	C2	A1
A1	C2	B2	A2	B2	A1	B2	B1	B1	B1	B2	A1	B2	A2	B2	C2	A1
A1	C1	B2	B1	C3	B2	A1	B2	A1	B2	A1	B2	C3	B1	B2	C1	A1
A1	C1	C3	B1	B2	A2	B2	A1	B2	A1	B2	A2	B2	B1	C3	C1	A1
	A1	C2	B1	C3	B2	C3	B2	C3	B2	C3	B2	C3	B1	C2	A1	
	A1	C1	C3	B1	B1	B1	A2	B2	A2	B1	B1	B1	C3	C1	A1	
		A1	C1	C2	C3	B2	B2	C3	B2	B2	C3	C2	C1	A1		
			A1	A1	C1	C1	C2	C2	C2	C1	C1	A1	A1			
					A1	A1	A1	A1	A1	A1	A1					

A1	2.25 wt% central zone enrichment (CZE) with no gadolinia
A2	2.25 wt% CZE with 4 rods at 4wt% gadolinia
B1	2.70 wt% CZE with 8 rods at 8wt% and 4 rods at 4wt% gadolinia
B2	2.70 wt% CZE with 12 rods at 8wt% and 4 rods at 2wt% gadolinia
C1	3.25 wt% CZE with 4 rods at 6wt% and 4 rods at 2wt% gadolinia
C2	3.25 wt% CZE with 8 rods at 6wt% and 4 rods at 2wt% gadolinia
C3	3.25 wt% CZE with 12 rods at 8wt% and 4 rods at 2wt% gadolinia

Fig. 2. Initial core loading map.