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Analysis of thorium fuel feasibility in large scale gas cooled fast reactor using MCNPX code

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ABSTRACT

In this paper thorium fuel feasibility in large scale Gas Cooled Fast Reactor (GCFR) is investigated. The neutronics benchmark used in this study, GFR2400, corresponds to a 2400 MWth GFR concept proposed by the French CEA. MCNPX computational code is used to design a 3D heterogeneous model of the GFR2400 core. A detailed feasibility analysis of the performance of thorium fuel cycle is performed by using thorium as an alternative fertile fuel for the natural uranium vector of the reference core design. The most essential neutronic parameters characterizing the core are determined both for beginning of life (BOL) conditions as well as during burnup. Also, a three-dimensional core cycle-by-cycle simulations is performed to allow explicit characterization of the core behavior and safety-related parameters during both open and equilibrium cycles. The thorium-based core shows favorable neutronic characteristics with an acceptable control and safety parameters for both BOL and open cycle states. The depressurization reactivity effect and core expansion coefficients (axial and radial) show improvement compared to the uranium-based core. However, this improvement is compensated by the deterioration in the effective delayed neutron fraction (β-eff) and the Doppler reactivity Effect. The results of isotopic transmutation and fuel burnup confirm the capability of the core to work in both open and closed cycles and to self-recycle its own MA vector and plutonium of LWRs. However-as is the case in other fast reactors including the uranium-based GFR2400 core, the fuel cycle closure causes safety related parameters to degrade.

1. Introduction

Currently, uranium based fuels are the basic materials considered for nuclear fission energy. However, to meet the increasing global energy demand it is important to utilize alternative resources such as thorium which is 3–4 times more abundant than uranium and is widely distributed in nature (IAEA, 2005). Thorium is transformed into the fissile U-233 material in both thermal and fast reactors, thereby enlarging the 'fissile' material resources. Also, thorium based fuel is considered to be a more attractive option than uranium fuels for burning nuclear waste as smaller quantity of plutonium and minor actinides (MA) are generated. A number of previous studies (Carrera et al., 2007; Chang et al., 2006; Herring et al., 2001) have demonstrated the feasibility of thorium utilization in thermal reactors. However, thorium fuel feasibility in fast spectrum reactors has not been fully demonstrated. Therefore, in the present study the feasibility of thorium fuel in the gas-cooled fast reactor (GCFR) is investigated.

The gas-cooled fast reactor is one of six candidates chosen by the Generation-IV Initiative for developing safe, sustainable, reliable, proliferation-resistant and economic nuclear energy systems (GIF, 2002). The neutron spectrum of the GCFR is considered to be the hardest among fast spectrum systems, making it ideal for recycling all actinides, including LWRs plutonium and minor actinides (MA). Recently, two reactor thermal powers, namely 600 Megawatts thermal (MWth) and 2400 MWth, are being considered as appropriate operating powers for the GFR concept (Farmer et al., 2006). The design of the GCFR concept has been under development during the last decade. This development included designs of different considered fuel forms such as coated fuel particle, silicon carbide blocks with dispersed microparticle fuel inside, and silicon carbide plates with fuel pellets arranged in honeycomb structure, finally arriving to the current design of a hexagonal fuel assembly composed of cylindrical rods, of fuel pellets, arranged in a

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hexagonal array and surrounded with a hexagonal SiC wrapper (Perko et al., 2015).

In the present study, MCNPX 2.7 Monte Carlo transport code (Pelowitz, 2011) is used to design a 3D heterogeneous core model of the 2400 MWth gas-cooled fast reactor core. This model corresponds to a promising concept called the GFR2400 "academic core" which has been proposed by the Commissariat à l'Énergie Atomique (CEA) in France. The GFR2400 is a highly innovative system with advanced geometry and fuel materials (Ceramic fuel pellets of mixed uranium-plutonium carbide within fuel pins). Furthermore, it is considered as a reference concept for a commercial size Gas-Cooled Fast Reactor. The objective of this work is to investigate the feasibility of a thorium based fuel cycle, with LWRs Pu used to ensure the necessary criticality. The most essential neutronic parameters characterizing the core have been determined for beginning of life (BOL) conditions as well as for open and equilibrium core cycles. Also several important safety-related quantities have been evaluated and the transmutational capabilities have been assessed.

The work presented in this paper is organized as follows: the core design and model validation are introduced in Section 2; the thorium fuel feasibility analysis including the thorium fuel specification and assessment of several neutronic and safety parameters at BOL conditions are discussed in Section 3; the main results, with a focus on fuel cycle aspects and safety parameters evolution, are presented in Sections 4 and 5, respectively. Future work and final conclusions are provided in Sections 6 and 7, respectively.

2. GFR2400 core modelling

The reference GFR model considered in this study is based on a 2400 MWth GFR concept, proposed by the French CEA (Richard et al., 2010; Perko et al., 2015). The design parameters of this model are presented in Table 1. It is utilizing pin fuel element and uses helium coolant at a high pressure of 7 MPa to ensure adequate heat transfer.

A layout of the designed GFR2400 core model is shown in Fig. 1. As shown the active fuel region of the core is composed of 516 hexagonal fuel assemblies (FAs) divided into two core zones namely, the inner core zone (IC) with 264 fuel assemblies, and the outer core zone (OC) with 252 fuel assemblies. The two core zones have different fissile enrichments namely, 14.12% for IC and 17.65% for OC, where the percentages represent the volume fraction of fissile plutonium material present in the fuel. Although the fuel pins are not presented individually within assemblies in Fig. 1, in all calculations the fuel assemblies are modelled rod by rod (heterogeneous).

Within the active core region, there are 18 controls shut down (CSDs or control rods) and 13 diverse shut down (DSDs or safety rods) assemblies to control the core during operation and to ensure its safety in case of accidents as well. Both assemblies are constructed in the same manner with the absorber material in both sets is made up by boron carbide (B_4C, with 90% ^{10}B) whereas the material of the structural elements is a special steel alloy (AIM1). For neutrons confinement, a 480 reflector assemblies are placed around the active core to prevent fission neutrons from escaping, along with two axial (upper and lower) reflector regions. The reflector material of both axial and radial reflectors is made up of Zr_3Si_2. Both control and reflector elements of the core have been modelled completely homogeneous as only their expected volumetric composition is determined (Table 2).

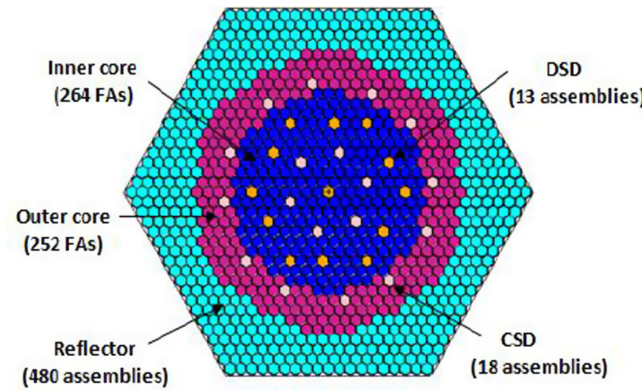

Fig. 1. A Layout of the GFR2400 core.

2.1. Fuel lattice design

Fig. 2 shows a cross sectional view (at fuel level) for both fuel assemblies and pin lattice configurations. As shown both fuel assemblies of the inner and outer core are composed of 217 fuel pins arranged in a hexagonal array and surrounded with a hexagonal SiC wrapper. The fuel in each pin is composed of uranium plutonium carbide (UC/PuC) pellets which extend for a length of 165 cm. Above and below the fuel region there are two empty plenum regions of lengths 85 and 50 cm, which are reserved for the confinement of fission gases. The axial reflector region extends for 1.0 m beyond both the upper and lower empty plenum regions. The reflector material is made of zirconium silicide (Zr_3Si_2), which is proved to withstand high temperatures. The cladding of the pins is made of SiC covered with thin metallic liners (rhenium and a tungsten rhenium-alloy) from the inside to increase fission products confinement. The detailed geometrical description of the GFR2400 fuel configuration at room temperature is summarized in Table 3.

Table 1
Basic operation parameters of GFR2400.

Reactor Parameter	Value
Thermal power [MW]	2400
Primary pressure [MPa]	7
Mass flow rate [kg/s]	1213
Core inlet temp. [°C]	400
IHX inlet temp. [°C]	346
Primary coolant	He
Pressure drop in core [MPa]	0.143
By pass flow rate [kg/s]	60
Core outlet temp. [°C]	780
Secondary pressure [MPa]	6.5

Table 2
Volumetric composition of homogeneously designed core elements.

Core element	Material	Volume fraction (%)
Radial reflector	Zr_3Si_2	80
	He (7 MPa)	20
Upper and lower reflector	Zr_3Si_2	60
	He (7 MPa)	40
Control and Shutdown rods (CSD and DSD)	B_4C (90% ^{10}B)	30.26
	He (7 MPa)	47.67
	SiC	10.85
	AIM1	11.22
Rod follower	SiC	10.85
	He (7 MPa)	87.95
	AIM1	1.20