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Core analysis of spectral shift operated SmAHTR

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ABSTRACT

Fluoride High-temperature Reactors (FHRs) are regarded for their high temperature output and passive decay heat rejection. Small Modular Advanced High Temperature Reactor (SmAHTR), a 125 MWth reactor falls under the FHR group. Along with FHRs, SmAHTR also uses multilayered, high accident tolerant TRistructural ISOtropic (TRISO) fuel kernels. Despite the reactor's benefits due to its high efficiency and safety parameters, its considerably higher fuel costs compared to traditional UO_2 fuel creates a drawback. To mitigate this problem and use the fuel more efficiently, lower fraction of fuel can be loaded into the core, however the resulting cycle length may be prohibitively short. This study proposes a spectral shift scheme to improve both the discharge burnup and the cycle length simultaneously for these types of reactors. Our analyses include both the neutronic and the thermal hydraulics (T/H) assessment for the non-spatial implementation of this scheme under single- and multi-batch scheme operation. The safety performance, *i.e.* reactivity coefficients and T/H limits, for this concept is comparable to the original design. The results confirm that performance benefits of more than 32% compared to the original design are achievable.

1. Introduction

Fluoride-salt-cooled High-temperature Reactors (FHRs) are thermal spectrum reactors operating at near-atmospheric pressure and high coolant temperatures (around 700 °C). These reactors use liquid-fluoride-salt as coolants, tri-isotropic (TRISO) coated fuel elements, and graphite as moderator (Forsberg, 2004). The thermal properties (*e.g.* heat capacity) of fluoride-salt coolants are advantageous for passive decay heat removal. TRISO fuel yields fission products to be accumulated within its layers, thus offering high accident tolerance against the release of fission products (FP) in the coolant.

Small Modular Advanced High Temperature Reactor (SmAHTR) is a compact 125 MWth thermal spectrum FHR proposed by Oak Ridge National Laboratory (ORNL) in 2010 (Greene, 2010). It is designed to deliver safe, affordable, and reliable high temperature process heat and electricity. The reactor vessel is envisioned to be truck transportable to practically any destination. Although the original ORNL design consists of three different fuel configurations, in this study, 19 hexagonal plate type fuel assembly was adopted due to its superior mechanical stability and integrity (Greene, 2010). It should be noted that the results and trends acquired in this study can still be applied to other fuel configurations. The latter observation is based on the analyses performed for other geometry types, which will not be shown in this paper.

Despite the safety benefits provided by the TRISO based fuel pellets, one of the significant drawback is the particle fabrication costs. The fabrication cost of TRISO based fuel is estimated to be between $5000 and $30,000 per kgU (Shropshire et al., 2009), which is much higher than the cost for UO_2 ($300 per kgU). For this reason, even a fractional gain in burnup provides a significant advantage in fuel cycle costs, which is the main motivation of this study.

The primary objective of this study is to increase the fuel utilization of the SmAHTR without reducing the cycle length. To achieve this goal, the implementation of spectral shift approach was investigated on the pre-conceptual SmAHTR design (Greene, 2010) with the modifications proposed by SmAHTR-CTC neutronic design (Ilas et al., 2014). In the spectral shift technique, movable graphite structures are incorporated in the design. At the beginning of life (BOL), a portion of these graphite structures are removed from the core; this, leads the core to experience a harder spectrum and breeding more ^{239}Pu. The graphite structures are then gradually inserted, while maintaining the reactor critical, to allow more moderation and thus burn the extra accumulated ^{239}Pu. As a result, this approach yields higher in-core residence time.

In this study, several variables able to affect both cycle length and burnup were investigated. These variables include the TRISO

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particle packing fraction (PF) within the graphite matrix, the carbon to heavy metal (CHM) ratio, lattice pitch between the fuel assemblies, and fuel enrichment. Previous studies (Kotlyar et al., 2017) proposed to implement the spectral shift control regime in the SmAHTR design. However, the mentioned research was merely a proof-of-concept, in which fixed design parameters were used (*e.g.* CHM ratio, PF). Our previous work (Mehta and Kotlyar, 2017a) focused on mimicking the spectral shift effect via density perturbation and the trade-offs studies to identify the optimum design space (*e.g.* CHM). Subsequently, movable graphite blocks were implemented to better understand the physical insertion regime (Mehta and Kotlyar, 2017b). The current research combines and extends all these studies by introducing the spectral shift control through movable graphite structures, rather than variation in graphite densities. This research also examines the possibility of incorporating a multi-batch operation scheme and provides applicable savings using this method. The current research also presents the burnable poison loading requirements for the original design, and the associated fuel cycle length penalties are estimated. Our results indicate significant improvement in both the fuel utilization, and the cycle length of the reactor compared to the original design as proposed in SmAHTR-CTC concept (Ilas et al., 2014).

For safety considerations, full core, plate-by-plate, thermal hydraulic (T/H) performance are evaluated for both the original and proposed designs. The results confirm that the maximum temperature peak is well below the pyro-carbon layer of TRISO particles limit of 1400 °C (Trejo et al., 2015). In addition, the current analysis compared the reactivity coefficients for the proposed and the original design, showing comparable values. Finally, the proposed and the original designs are compared with respect to their economic performance and above 30% savings are found.

2. Codes and methods

2.1. Serpent

The reported analyses relied on Serpent, which is a continuous-energy Monte Carlo reactor physics burnup calculation code (Leppänen et al., 2015). Serpent provides a built-in functionality to generate randomized particles distribution using the SHAKE algorithm. Serpent uses a Woodcock delta-tracking method which makes the computational time much faster compared to the conventional methods such as surface-to-surface ray-tracing implemented by most codes (Leppänen, 2010). An external criticality search algorithm, *i.e.* graphite insertion scheduler, was implemented in an external computational routine and coupled with Serpent. The spectral shift operation was simulated by this coupled code. Serpent was used to perform the reactor physics calculations and output the criticality values for a specific depletion step, and the criticality search algorithm was used to adjust and insert a portion of the graphite structures to maintain a near-to-critical state. This process is repeated until 100% of the graphite is inserted and the core is no longer critical. The coupled code was used for both the sensitivity studies as well as the physical insertion analysis of this paper.

2.2. Thermo

The THERMO module was developed for the coupled MC BGCore code (Kotlyar et al., 2011) to provide TH feedback by calculating fuel, gap, cladding and coolant temperatures and densities at predetermined burnup steps. The module is suitable for analyzing a wide range of geometries, such as square or triangular pitch fuel pin lattices and block-type fuel. In the current research, a plate-type geometry was added to the calculation sequence. In addition, a thermo-physical properties database for diverse coolant, fuel and structural materials of current reactors is readily available. For this study, the database was extended to include the properties of silicon carbide (SiC) (Snead et al., 2007) and FLiBe (Williams, 2006, Sohal et al., 2012, Zaghloul et al., 2003).

The methodology relied on calculating the pressure losses in separate T/H channels. Friction, form, acceleration and gravity pressure losses are all accounted for in the T/H analysis. Since the pressure drop distribution among parallel coolant channels must be identical, an iterative routine to calculate the mass flow rate distribution is implemented. The iterative approach relies on the Newton-Raphson method to obtain uniform pressure losses in all channels through variation of the flow rate in each channel. The procedure starts with uniform mass flow rate guess and stops when the relative difference between the minimum and maximum pressure loss values is below 0.1%.

2.2.1. Radial conduction model

The temperature distribution within the fuel meat, sleeve and coolant elements relied on several assumptions. The primary of which assumed that there is no heat conduction in the axial direction and only 1-D conduction is assumed. Non-uniform spatial power distribution within the fuel element was considered. The temperature distribution in the plank fuel meat surrounded by the FLiBe coolant is obtained by solving the general steady-state 1-D heat conduction equation:

$$\frac{d}{dx}\left[k(T)\frac{dT}{dx}\right] + \mathrm{q}''' = 0 \tag{1}$$

The inner wall fuel temperature (*i.e.*,$\mathrm{T_f}$) at the fuel surface (*i.e.*, $x = a$) is obtained using:

$$T_f = \left(\frac{1}{h} + \frac{\delta_s}{\mathrm{k_s}}\right) \cdot q'' + T_\infty \tag{2}$$

where, h is the heat transfer coefficient, k_S is the conductivity of the graphite sleeve and δ_s is the thickness of the sleeve. The power density, q''', in each layer is known directly from Serpent. The bulk FLiBe coolant temperature is sequentially updated for each axial layer.

Finally, the maximum fuel temperature of the TRISO particles at the center of the slab ($\mathrm{x} = 0$) is calculated by applying:

$$\int_{T_f}^{T_m} k_{fuel}(T)dT = \frac{q'''}{2}\mathrm{a}^2 \tag{3}$$

In order to solve and evaluate the fuel temperature distribution within the fuel (between $x = 0$ and $\mathrm{x} = \mathrm{a}$), it is divided into 10 equal-volume 1-D layers and Eq. (3) is solved iteratively until a converged fuel temperature distribution is achieved.

2.2.2. T/H properties

This section presents the properties used in this study. The thermal conductivity of the fuel meat, *i.e.* TRISO particles embedded within a graphite matrix, was estimated according to a model described by Lewis (1967). The thermal conductivity of uranium dioxide was obtained from the mentioned study and is represented by the following relation:

$$k_{UO_2}\left[\frac{W}{m^\circ K}\right] = \begin{cases} 10.41 - 9.44 \times \frac{T}{10^3} + 2.52 \times \left(\frac{T}{10^3}\right)^2 & T < 1800 \\ 1.73 & T \geq 1800 \end{cases} \tag{4}$$

The thermal conductivities for the graphite and silicon carbide were fitted according to the data points presented by Matsuo (2000) and Snead et al. (2007) and the correlation are presented in Eqs. (5) and (6), respectively.