Annals of Nuclear Energy 104 (2017) 53–63

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Improving fuel utilization in SmAHTR with spectral shift control design: Proof of concept

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ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 16 December 2016
Accepted 20 December 2016
Available online 23 February 2017

Keywords:
Small Advanced High-Temperature Reactor (SmAHTR)
Fluoride-cooled High-temperature Reactor (FHR)
TRistructural ISOtropic fuel (TRISO)
Spectral shift effect
SERPENT

ABSTRACT

This paper presents a spectral shift design based approach to improve the fuel utilization factor or alternatively to increase the cycle length in a graphite moderated reactor. The feasibility of this concept was tested in the Small Advanced High-Temperature Reactor (SmAHTR). This is a small sized Fluoride-salt-cooled high-temperature reactor (FHR) that uses tri-isotropic (TRISO)-coated particle fuels and graphite moderator materials. A major benefit of the TRISO particles is the ability to mitigate fission product release in the case of an accident. However, the fabrication costs associated with TRISO particles are expected to be significantly higher than the traditional UO_2 fuel. The preliminary studies presented in the paper are focused on extending the achievable irradiation period without increasing the value of the enrichment. In order to increase the discharge burnup, the design includes graphite structures that are initially removed from the core. This imposes a harder spectrum, which enhances the breeding of ^{239}Pu. Then, the graphite structures are gradually and continuously inserted into the core to sustain criticality. This procedure shifts the hard spectrum into a more thermal one and enables a more efficient utilization of ^{239}Pu. The preliminary results indicate that this design achieves considerably longer irradiation periods and hence lower fuel cycle costs than the reference design.

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1. Introduction

Fluoride-salt-cooled high-temperature reactors, often referred to as FHRs, are a new class of thermal-spectrum nuclear reactors defined by their use of liquid-fluoride-salt coolants, together with tri-isotropic (TRISO)-coated particle fuels and graphite moderator materials (Forsberg, 2004).

The liquid salt coolant is advantageous for passive decay heat removal, as the liquid salt can still efficiently remove decay heat in the event that the primary circuit is depressurized. There is also a lower temperature difference across the core, leading to improved thermodynamic efficiency relative to gas-cooled reactors. The proposed salt is a mixture of lithium fluoride and beryllium fluoride (‘FLiBe’). One of the main advantages of the FLiBe is its high boiling point, which is above 1400 °C. Moreover, it also has a high volumetric heat capacity of 4670 kJ/m^3 °C (Greene, 2010). These features allow the FHR to possess very high core power density and to operate at significantly low system pressure (less than 1 MPa) while producing a high outlet temperature, more than ~700 °C. Furthermore, this high operating temperature expands the functionality of the reactor for other high temperature applications such as hydrogen production. Nevertheless, the main disadvantage of the FHR is the requirement for a novel coolant, which introduces potential corrosion issues and leads to the production of undesirable activation products (e.g. tritium).

The Small Advanced High Temperature Reactor (SmAHTR) is a small modular version of the FHR developed by ORNL (Greene, 2010; Ilas et al., 2014). It has a thermal power of 125 MW. It is envisaged to have 19 fuel assembly columns in a hexagonal layout.

A single batch fuel management strategy is envisaged, with the entire core being discharged at the end of the cycle. While maximising cycle length, which is desirable for small modular reactors, this penalises the achievable discharge burn-up by approximately 33% relative to a 3-batch strategy (Driscoll et al., 1990).

In this paper, the possibility of using the ‘spectral shift’ concept to increase the fuel utilization of the SmAHTR without penalizing the cycle length is investigated. This is achieved by incorporating movable graphite structures into the design, instead of the static graphite blocks presently envisaged. At beginning of life (BOL), the graphite structures are withdrawn. The reactor is substantially under-moderated, with excess neutrons being primarily captured

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http://dx.doi.org/10.1016/j.anucene.2016.12.037
0306-4549/Published by Elsevier Ltd.

in ^{238}U, breeding ^{239}Pu. Towards the end of life (EOL), the graphite structures are inserted, thermalizing the neutron spectrum and increasing reactivity. The extra ^{239}Pu bred during the cycle is then burned, allowing the cycle to be extended. It is thought that such movable structures should be feasible from an engineering point of view, given that it is broadly equivalent to inserting and withdrawing control rods.

The preliminary results presented here indicate that such a design may considerably improve the fuel utilization (i.e. by more than 40%). Further studies will consider the practical implementation of this concept.

2. Codes

The analyses reported here were performed with Serpent (Leppänen et al., 2015). The Monte Carlo based Serpent code has been extensively verified (Leppänen et al., 2014). Serpent has a built-in fuel depletion solver (Pusa and Leppänen, 2010) that is based on the Chebyshev rational approximation (CRAM) method (Pusa, 2011). The code was developed as an alternative to deterministic lattice physics codes for generation of homogenized multi-group constants (Fridman and Leppänen, 2011; Dorval and Leppänen, 2015) for reactor analysis using nodal codes. However, the range of applicability of Serpent is increasing, at it is for example used in multi-physics calculations (Ikonen et al., 2015). The code achieves more efficient CPU time performance compared to some other Monte Carlo codes due to the code's implemented routines. Among these features are unified energy grid (Leppänen, 2009) and the use of Woodcock delta-tracking (Leppänen, 2010) of particles. The current version of Serpent contains various evaluated data libraries (e.g. JEF-2.2 and JEFF-3.1), with ENDF/B-VII.0 being used in the current study.

The analysis of the proposed SmAHTR core design (Section 4) were performed using an external criticality search algorithm for scheduled graphite insertion (Section 5) that sequentially executed Serpent.

3. Oak-Ridge SmAHTR design description

3.1. General description

SmAHTR is an FHR-type reactor that aims to produce electricity with a high thermal efficiency, and also high-temperature process heat. The SmAHTR reactor vessel is transportable via standard tractor-trailer vehicles to its deployment location (more related to USA). SmAHTR is a thermal-spectrum nuclear reactor that employs graphite as its primary moderator material. The concept also uses the liquid-fluoride-salt coolant and is designed to operate with a core outlet temperature of 700 °C and nearly atmospheric pressure. The overall design approach can be adapted to much higher temperatures as soon as structural materials become available.

SmAHTR employs uranium oxicarbide (UCO), tri-isotropic (TRISO) particle fuel. In TRISO particle fuel, the fuel material, $UC_{0.5}O_{1.5}$ in this design, is in the form of small spheres that are sequentially over-coated with a series of protective layers. The particles are embedded within a graphitic material to form fuel compacts (Fig. 1).

Three different fuel forms have been investigated by the Oak Ridge team, cylindrical, annular and plate type. The cylindrical fuel form was evaluated first and an acceptable core form was developed. An annular concept was next investigated as a means to improve the thermal coupling between the fuel and coolant. The annular fuel form decreases the fuel peak operating temperature as compared to the cylindrical form. In order to provide strong mechanical mounting of the fuel, a plate fuel form was also considered. According to the report produced by Oak Ridge, the annular form design achieved the most favorable irradiation period of ~4.19 years. Therefore, it was decided to limit the analysis conducted here to this annular design, as described in Section 3.2. The sole purpose of this study is to examine the favorability in 'spectral shift' operation regime. Such an operation regime can be easily applied on various FHR designs without changing the trends.

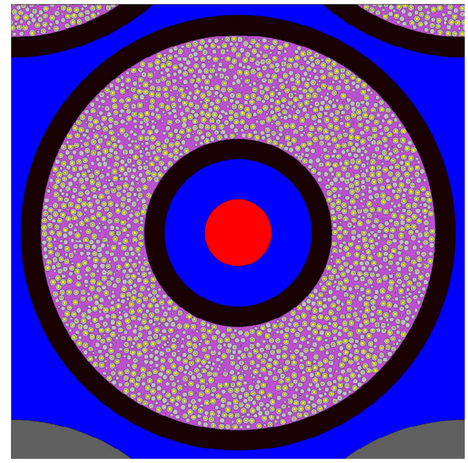

Fig. 1. Annular fuel pin. TRISO particles are indicated by the yellow circles, which are embedded in the graphite matrix (purple color). The center red circle is the tie rod. Inner and outer sleeves are colored in black and the coolant is blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Reactor fuel and core

The annular SmAHTR core uses 80 cm tall hexagonal fuel blocks stacked five high. In the annular fuel SmAHTR core variant, the fuel is configured into annular compacts roughly 5 cm high that are strung along a carbon–carbon composite vertical tie rod. The TRISO UCO fuel kernels are 500 μm in diameter. A total of 1,806.7 kg of uranium (19.75 wt% ^{235}U) is loaded into the core with a 50% volumetric packing factor of TRISO particles within the graphite matrix (Fig. 1). The graphite blocks are 45 cm across the flats. Each fuel block contains 15 fuel pins and 4 graphite pins. A cross section view of an annular fuel bundle within its graphite channel is shown in Fig. 2. The dimensions of the annular fuel bundle and

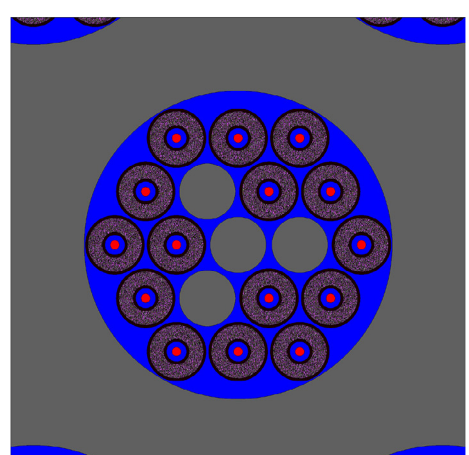

Fig. 2. Annular fuel bundle cross section with graphite (grey color) channel.