Pebble-Bed Core Design Option for VHTRs – Core Configuration Flexibility and Potential Applications

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Abstract

Gas-cooled nuclear reactors have been receiving specific attention for Generation IV possibilities due to desired characteristics such as relatively low cost, short construction period, and inherent safety. Attractive inherent characteristics include an inert, single phase helium coolant, refractory coated fuel with high temperature capability and low fission product release, and graphite moderator with high temperature stability and long response times. The passively safe design has a relatively low power density, annular core, large negative temperature coefficient, and passive decay heat removal system.

The objective of the U.S. DOE NERI Project is to assess the possibility, advantages and limitations of VHTRs with fuel loadings containing minor actinides. This paper presents the analysis of pebble-bed core configurations.

Whole-core 3D models for pebble-bed design with multi-heterogeneity treatments in SCALE 5.0 are developed to compare computational results with experiments. Obtained results are in agreement with the available HTR-10 data. Actinide fueled VHTR configurations reveal promising performance. With an optimized pebble-bed model, the spectrum shifting abilities become more apparent. Effects of altered moderator to fuel ratio, Dancoff factor, and core and reflector configurations are investigated. This effort is anticipated to contribute to a facilitated development of new fuel cycles in support of future operation of Generation IV nuclear energy systems.

KEYWORDS: HTGR, VHTR, Dancoff factor, spectrum shifting, advanced fuel cycles

1. Introduction

The objective of the U.S. DOE NERI Project is to assess the possibility, advantages and limitations of VHTRs (Very High Temperature Reactors) with minor actinides. The present analysis takes into consideration and compares capabilities of pebble-bed core designs in various configurations in preparation for analyzing minor actinides as a fuel component to approach the reactor lifetime long operation without intermediate refueling. [1].

The high temperature gas cooled reactor is the reactor type with which the coolant temperature can be as high as over 700ºC. This feature allows not only for power generation with a high efficiency, but also for the supply of heat in a variety of industrial applications. Models of the entire pebble-bed core considering multi-heterogeneity

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treatment have been developed in SCALE 5.0 for benchmark purposes to compare with other computational results and experimental data. Studies of the model for code-to-code and code-to-experiment benchmarks are underway and will be furthered to account for core streaming effects. Core and reflector configurations, effects of altered Dancoff factor, followed by dummy graphite pebble mixing will be further investigated.

The pebble-bed configuration is one of the probable VHTR designs currently being investigated alongside the prismatic core to evaluate strengths and drawbacks of each design.[2] The main advantages of the pebble-bed VHTR configuration are their capabilities for spectrum shifting, inherent safety features, autonomous operation, incredibly high burn-up, and higher efficiency. If successful in utilizing minor actinides from spent LWR fuel, there will be a reduced spent fuel flow and handling per unit of produced energy. If widely deployed, the developed designs would allow reducing the long term radiotoxicity and head load of high-level waste sent to a geologic repository and enable recovery of the energy contained in spent fuel. From the larger perspective, VHTR configurations can increase competitiveness and marketability of a Generation IV system. These systems allow for hydrogen production and possible deployment in developing countries. With minor actinides as a fuel component, the need for additional repositories would be significantly reduced.

The preliminary neutronics analysis of the ability to shift the neutron spectrum in the pebble-bed VHTR configuration is presented in this paper. The spectral shift was archived by adjusting moderator-to fuel ration of the pebble-bed core. It is shown that the minor actinides as a fuel component achieve a higher burn-up in the fast spectrum. [3] Although a high destruction rate of minor actinides is envisioned as one the inherent characteristics of ultra-long life VHTR cores considered in this study, transitions between different spectral regimes would be required to optimize use of minor actinides and to maintain self-generation during the entire reactor lifetime.

2. Modeling Approach

Computational issues are addressed when combining Monte Carlo and deterministic approaches while applying multi-heterogeneity treatment. The code used in these calculations is SCALE 5.0 which uses cross section data based on ENDF/B-V evaluation. [4]

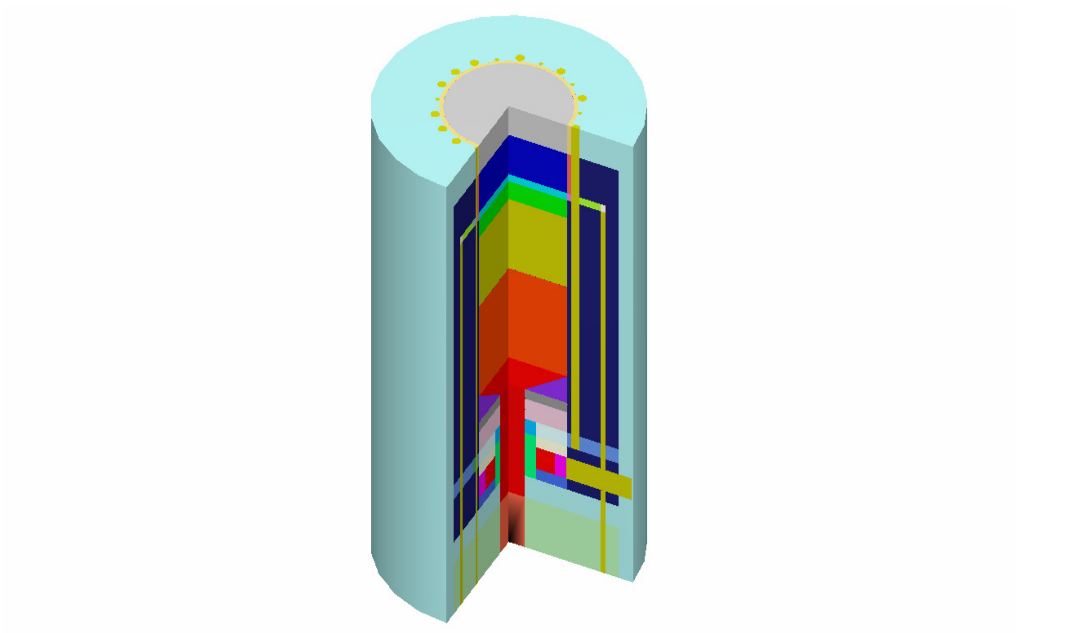
SCALE 5.0 was used to model the high temperature gas cooled reactor (HTGR) pebble-bed design and benchmarked against PROTEUS experiments. It will further be used to achieve results through variations on moderator to fuel ratio, Dancoff factor, and other sensitivity analyses. Later approaches will be considered to the possibility of minor actinides as fuel components in pebble-bed HTGR designs.

SCALE 5.0 utilizes cross section data based on ENDF/B-V evaluation and the 238-group library. SCALE is a modular code system for Standardized Computer Analysis for Licensing Evaluation. It has been developed by Oak Ridge National Laboratory and utilizes well-established computer codes and methods within standard analysis sequences. SCALE 5.0 has several significant new modules to allow performing calculations of continuous energy spectra for processing multigroup problem-dependent cross sections, 1D and 3D sensitivity and uncertainty analyses, and 2D flexible mesh discrete ordinates modeling. KENO-VI is a version of KENO Monte Carlo criticality safety code which constructs and processes geometry data as sets of quadratic equations. The code's flexibility is increased by allowing intersection geometry regions.

The HTR-10 is a pebble-bed HTGR containing about 27,000 spherical fuel elements with ceramic coated fuel particles. The reactor core has a diameter of 1.8 m, a mean height of 1.97 m and a volume of 5.0 m^3, and is surrounded by graphite reflectors. The core is made up of spherical fuel elements of radius 6.0 cm with TRISO coated fuel particles embedded in a graphite matrix. Graphite serves as the main material of core structures which mainly consist of top, bottom, and side reflectors.

For the initial core loading, dummy balls (graphite balls without nuclear fuel) will be placed into the discharge tube and the bottom conus region of the reactor core. Then, a mixture of fuel balls and dummy balls will be loaded to approach criticality. The percentage of fuel balls (57%) and dummy balls (43%) is envisaged. After the first criticality is reached, mixed balls of the same ratio will be further loaded into the full core. The benchmark problems include core physics evaluation at initial criticality at 23°C, 120°C, and 250°C, control rod worth (for initial and full core) and the temperature coefficient. Figure 1 illustrates the 3D reactor physics model.

Figure 1: KENO3D Model of Pebble-Bed VHTR Configuration for Benchmarking Purposes.



2. Minor Actinide Characteristics

Using minor actinides in fuel design requires understanding nuclear interactions and characteristics. These characteristics greatly affect production and burn-up in a nuclear reactor. There are several nuclear data libraries which are not entirely consistent with one another. Ten nuclides including uranium, neptunium, americium, and curium are compared using characteristics such as capture cross section, fission cross section, neutron production per fission, neutron production per absorption, capture to fission ratio, and delayed neutron fraction. Table 1 displays these characteristics as a ranking for all nuclides with one representing the largest value for that characteristic and ten as the smallest. The characteristics examined in Table I are supplemental to the process of shifting a pebble-bed spectrum to a desired position. When investigating the spectrum shifting possibilities, the nuclear characteristics such as fission cross section and neutron capture to fission ratio are important.

Table 1: Minor Actinide Nuclear Characteristic Rankings.

	σ_f	σ_c	ν_f	η	A	B (% of ^{238}U)
^{235}U	3	6	1	4	9	38.82%
^{238}U	10	10	9	10	1	100%
^{237}Np	9	4	8	9	2	23.23%
^{241}Am	6	2	7	7	4	7.47%
^{242m}Am	1	1	6	3	8	11.97%
^{243}Am	8	7	5	8	3	13.76%
^{242}Cm	5	8	3	5	6	2.24%
^{243}Cm	4	5	4	2	7	4.97%
^{244}Cm	7	9	2	6	5	N/A
^{245}Cm	2	3	1	1	10	10.08%

3. HTR-10 Benchmark Problems

The benchmark problems performed for the HTR-10 in this report include reactor core physics evaluation for initial criticality, and initial and full core control rod worth. The core physics model includes structures only until carbon bricks.

The effective multiplication factor for the full core was evaluated at 300, 393, and 523K. For this calculation the core is under a helium atmosphere without control rods inserted.

The results are summarized in Table 2. [5]

Table 2: Full Core Effective Core Multiplication Factors.

Benchmark	VHTR (Homogeneous)	HTR-10
20℃	1.2558±0.0018	1.1358
120℃	1.2349± 0.0019	1.1262
250℃	1.2222±0.0028	1.1111

4. Spectrum Shifting Through Dummy Graphite Pebble Mixing

Pebble-bed cores exhibit possible flexibility in component configuration. This enables improvement of fissile properties of minor actinides (as shown in Table 1) as a result of neutron spectrum shifting. This makes it possible for certain actinides to serve as fuel materials or burnable poisons over prolonged irradiation periods.

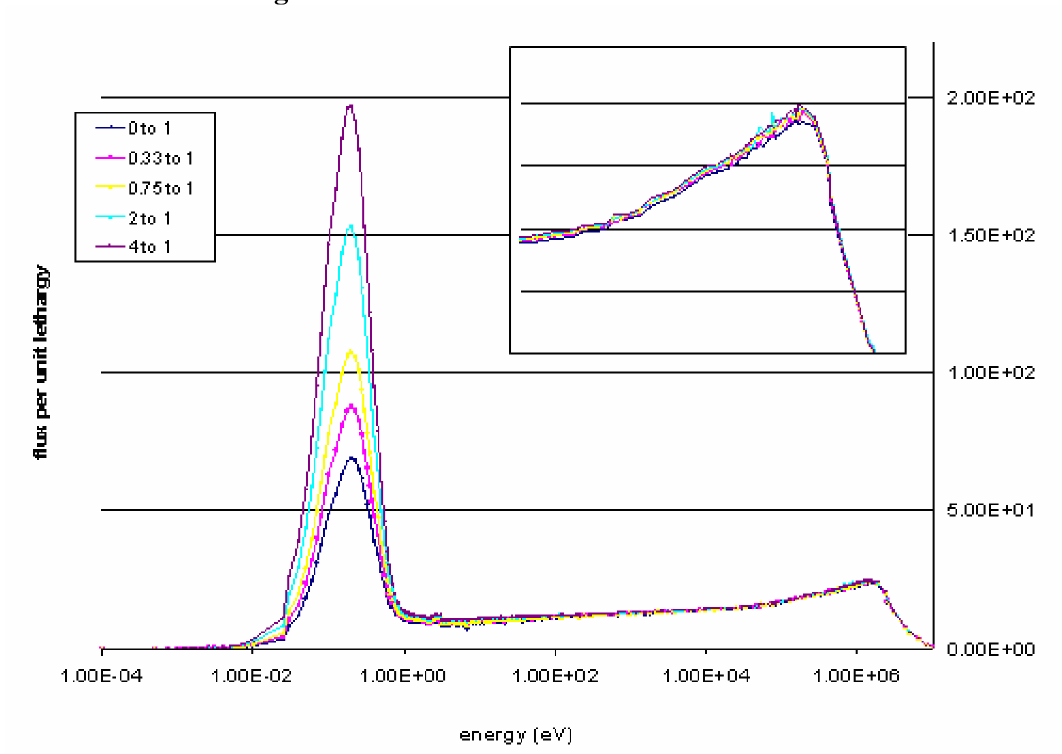
By mixing dummy graphite pebbles and fuel pebbles, specific spectral characteristics can be varied.

Figure 2 displays the effect of varying fuel loadings on neutron flux.

5. Conclusions

Since the pebble-bed design allows flexibility in configuration adjustment, fuel utilization, and fuel management, it is possible to improve fissile properties of minor actinides by neutron spectrum shifting. This research effort enhances capabilities of the Generation IV VHTRs. This technology also displays promising aspects in economical analyses due to high burn-up, autonomous operation, and a potential for actinide recycling.

Figure 2: Moderator-to-Fuel Pebble Ratio Variations.



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