Self-Sustainability of VHTR Configurations with Advanced Actinide Fuels

Pavel V Tsvetkov*, David E. Ames II, Ayodeji B. Alajo and Megan L. Pritchard
Department of Nuclear Engineering, Texas A&M University, 129 Zachry Engineering Center, MS 3133 TAMU, College Station, Texas, 77843-3133, USA

Abstract

Minor actinides represent the long-term radiotoxicity of nuclear wastes. As one of their potential incineration options, partitioning and transmutation in fission reactors are seriously considered worldwide. If implemented, these technologies could also be a source of nuclear fuel materials required for sustainability of nuclear energy.

The objective of the U.S. DOE NERI Project is to assess the possibility, advantages and limitations of achieving ultra-long life VHTR (Very High Temperature Reactor) configurations by utilizing minor actinides as a fuel component. The analysis takes into consideration and compares capabilities of pebble-bed and prismatic core designs with advanced actinide fuels to approach the reactor lifetime long operation without intermediate refueling.

This paper discusses the up-to-date research efforts. Whole-core/system 3D models with multi-heterogeneity treatments and property databases of actinide compounds are developed together with relevant benchmark problems to compare computational results with experiments. Obtained results are in agreement with the available HTTR and HTR-10 data. Studies of actinide-fueled VHTR configurations indicate promising performance characteristics. Utilization of minor actinides as a fuel component would facilitate development of new fuel cycles and support sustainability of a fuel source for nuclear energy assuring future operation of Generation IV nuclear energy systems.

KEYWORDS: HTGR, VHTR, transmutation, minor actinides, spectrum shifting, advanced fuel cycles

1. Introduction

Industrial nuclear power was introduced in the United States in the 1950s. Today it provides approximately 20 percent of the United States' electricity generation and about 17 percent of the world's electricity generation. Nuclear power has proven to be an environmentally safe, reliable, and economical to generate large supplies of electricity without releasing noxious gases into the atmosphere. A key roadblock to expansion of nuclear power is the concern over management of the spent nuclear fuel.

Partitioning and transmutation in fission reactors are seriously considered worldwide as potential incineration options. [1] U.S. DOE Advanced Fuel Cycle Initiative (AFCI) program is developing the technology base for waste management including partitioning and transmutation. Successful deployment of these technologies could also result in a source of nuclear fuel materials.

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* Corresponding author, Tel. 1-979-845-7078, Fax. 1-979-845-6443, E-mail: tsvetkov@tamu.edu

The United States Department of Energy has given priority to the Very High Temperature Reactor (VHTR) concept making it the focus of intensive research programs. The VHTR is a graphite moderated gas-cooled reactor that supplies heat with core outlet temperatures equal to or greater than 850 degree Celsius, which enables applications such as hydrogen production, process heat for the petrochemical industry or others, or sea water desalination. Its basic technology has been well established in former High Temperature Gas Reactors (HTGR), such as the German AVR and THTR prototypes, and the US Fort Saint Vrain and Peach Bottom prototypes. The VHTR extends the capabilities HTGRs to achieve further improvements in thermal efficiency and open up additional high-temperature applications.

The objective of the U.S. DOE NERI Project is to assess the possibility, advantages and limitations of achieving ultra-long life VHTR configurations by utilizing minor actinides as a fuel component. The analysis takes into consideration and compares capabilities of pebble-bed and prismatic core designs with advanced actinide fuels to approach the reactor lifetime long operation without intermediate refueling. The ultra-long life VHTR systems are developed and analyzed focusing on control, dynamics, safety, and proliferation- resistance during reactor lifetime long autonomous operation.

Whole-core models with multi-heterogeneity treatments and property databases of actinide compounds have been developed together with relevant benchmark problems to compare computational results with experimental data. Code-to-code and code-to-experiment benchmark studies of the models and computational schemes are underway as well as analysis of the actinide-fueled VHTR configurations.

Utilization of minor actinides, from light water reactor (LWR) fuel, as a fuel component would facilitate development of new fuel cycles and support sustainability of a fuel source for nuclear energy assuring future operation of Generation IV nuclear energy systems. The ultra-long core life approach reduces the technical need for additional repositories. The proposed configurations can dramatically improve marketability and competitiveness of the Generation IV VHTR system for hydrogen production because their implementation allows worldwide deployment including developing countries. Furthermore, it is anticipated that the ultra-long core life approach would substantially reduce the technical need for additional repositories per decade of reactor operation. Utilization of minor actinides as a fuel component would facilitate development of new fuel cycles and support sustainability of a fuel source for nuclear energy assuring future operation of Generation IV nuclear energy systems.

2. Technical Approach and Methodology

2.1 Applied codes

Most of the available well-established and validated computer code systems are oriented on light water reactors (LWRs). To apply them for VHTRs, a specialized approach of application is required. Specifically, several technical challenges are associated with the analysis and development of ultra-long life VHTR configurations with minor actinides as a fuel component:

- whole core/system modeling with multi-heterogeneity treatments,
- model benchmarking, uncertainty effects of nuclear data and design parameters including temperature dependence,
- error propagation during depletion calculations,
- large computational times affecting ability to consider many design configurations.

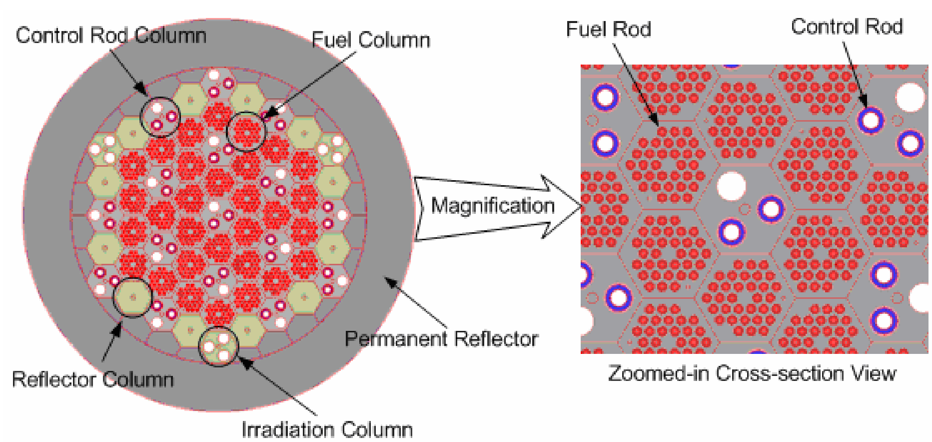
In the present study, state-of-the-art computer code systems are utilized to create realistic modeling of the VHTR configurations. These include the SCALE (Standardized Computer

Analysis for Licensing Evaluation) version 5 modular code system and Monte Carlo Calculations of Dancoff factors in irregular geometries [2,3]. Two separate models are created; one being the prismatic graphite block type core design and the other the pebble-bed type core design.

The prismatic core model is based on available information for Japan's operating High Temperature Test Reactor (HTTR). The HTTR was selected because of the reference material available. The reference material provided: general design features, reactor layout, core configuration, material properties, and other relevant information to develop the computational model. Also supplied were actual experimental test results to be utilized for experiment-to-code benchmarks and several analytical code results for code-to-code benchmark tests.

The VHTR model is a nearly explicit representation of the existing HTTR core configuration. The model was created in the SCALE code system utilizing the CSAS6/KENO-VI module, which allows flexible geometry representations. The geometry package in KENO-VI is capable of modeling any volume that can be constructed by quadratic equations (second order surfaces). KENO 3D was used to provide an actual cross-sectional view of the model, as shown in Fig. 1.

Figure 1: Horizontal Cross-section of VHTR/HTTR Model (KENO 3D).

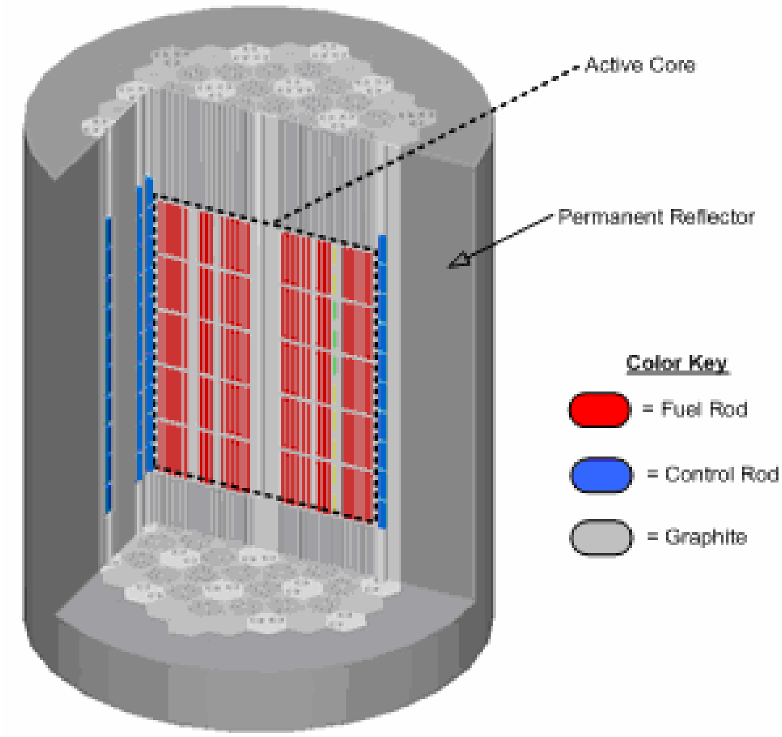


The general procedure for creating the model was to build the four types of prismatic hexagonal blocks that compose the HTTR, then to arrange these blocks in an array of rows and columns to construct the core. The completed computational model has over 8,500 lines. There are 7,290 geometry regions in the model.

The four prismatic blocks are: fuel assembly blocks, replaceable reflector blocks, control rod guide blocks, and irradiation blocks. The complete VHTR model has an overall height of 522 cm and a diameter of 430 cm. The fueled region or active core is 290 cm in height and 230 cm in effective diameter. All components are modeled explicitly, with the exception of the fuel compacts. The fuel compact consists of TRISO coated fuel particles embedded within a graphite matrix in the form of an annular rod. In the computational model, the TRISO fuel particles are homogenized with the graphite matrix of the fuel compacts. Double heterogeneity effects are accounted for using DANCOFF-MC code system. [3]

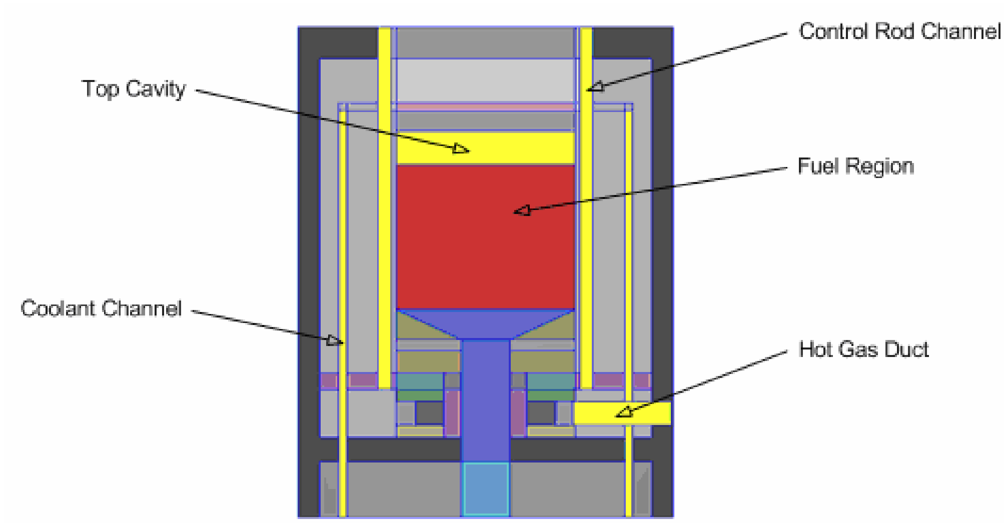
Figure 2 is a 3D cutaway view of the VHTR model, which shows the active core. In this particular figure the control rods are fully inserted in the core. There are 16 pairs of control rods, 7 in the active core and 9 in the replaceable reflector region.

Figure 2: 3D Cutaway View of VHTR/HTTR Model (KENO 3D).



The pebble-bed core is based on China's operating High Temperature Test Module (HTR-10). The pebble bed core consists of a fuel region (active core) that has a diameter of 180 cm and a height of 197 cm. The fuel region is surrounded by graphite reflectors, which consist of top, bottom, and side reflectors. A vertical cross-sectional view of the modeled structure is shown in Fig. 3.

Figure 3: Vertical Cross-sectional View of VHTR/HTR10 Model (KENO 3D).



The existing HTTR and HTR-10 configurations serve as the initial prototype designs and as examples of small-scale VHTRs.

A special effort is made to verify that the computational modeling is consistent and realistic. The results describe performance of the entire VHTR power unit and allow conclusions regarding the configuration's feasibility, performance and possible directions for further analysis and development. Following the international benchmark practices and accepted accuracy standards, the models require validated by experiment-to-code and code-to-code benchmarking procedures, with the goal of 10 percent prediction accuracy or better in computational studies. If results demonstrate higher discrepancy, but the discrepancy can be adequately explained by the model assumptions, then it will be concluded that the experimental benchmark testing is passed conditionally. In any case the ability to explain differences between code and experiment results is expected.

The key technical issues are being addressed and resolved by implementing computationally efficient automated modeling procedures and sequences, combining continuous energy Monte Carlo and multigroup Monte Carlo and deterministic approaches, developing and applying realistic 3D coupled neutronics-thermal-hydraulics models with multi-heterogeneity treatments, developing and performing experimental/computational benchmarks for model verification and validation, analyzing uncertainty effects and error propagation. [2-4]

2.2 Validation and Verification

To assure comprehensive, realistic assessment of the VHTR design and operation targeting passive safety confirmation, the adequacy of computational methods and models used to compute performance characteristics must be supported by comparisons with experimental data covering an appropriate range of conditions. Validation data are available from power reactors as well as past critical experiments.

As the basis for development of the benchmark test problems, the project uses the actual test results and developed benchmark problems of the LEU-HTR PROTEUS Program (pebble-bed criticality experiments), the HTTR Program (prismatic core design, reactor experiments), and the HTR-10 Program (pebble-bed core design, reactor experiments). [5] The benchmark problems are related to start-up core physics tests and include the analysis of the effective multiplication factor of fully loaded core with control rods fully withdrawn and fully inserted, control rod position at criticality, and isothermal temperature coefficient of reactivity.

All calculations were performed for a core temperature of 300K unless otherwise specified. A Dancoff correction factor of 0.8493, as calculated by DANCOFF-MC, was used for all benchmark tests.

Following the established international benchmark program practices, in the present analysis 10% discrepancy between computed values and the available experimental values was considered as the model acceptability threshold. In addition to experiment-to-code benchmark studies, code-to-code benchmark analysis was also performed to provide further understanding of the modeled system performance.

The results of the analysis showing comparison to experimental data are summarized in Table 1. The experiment-to-code benchmark analysis resulted in successful validation of the VHTR prismatic core model. Obtained computational results are in agreement with the available experimental data. The case for control rods fully withdrawn resulted in a discrepancy of about 1%. The observed larger deviation of computational results from experimental values occurred when the control rods were fully inserted, resulting in a 6%

discrepancy. This is due to ambiguity of available information regarding the control rods and core configuration. The benchmark case for the critical insertion depth of control rods, which translated to the control rods being inserted roughly halfway into the core, predictably reduced the discrepancy by about half.

Table 1: HTTR Model Experiment-to-Code Benchmark Analysis.

Benchmark		VHTR model (calculated)	HTTR (experimental)	Error (%)
Control Rods Fully Withdrawn	k_{eff}	1.1255 ± 0.0018	1.1363 ± 0.041	-0.95
Control Rods Fully Inserted	k_{eff}	0.7254 ± 0.0018	0.685 ± 0.010	+5.90
Critical Insertion Depth of Control Rods (core temperature 300K)	cm	181.6	177.5 ± 0.5	+2.31
Critical Insertion Depth of Control Rods (core temperature 418K)	cm	195.7	190.3 ± 0.5	+2.84
Temperature Coefficient α_T	Δ k/k/K	(-1.61 ± 0.25) E-4	-1.42E-4	+13.38

The computed value of the isothermal temperature coefficient deviates by 13% from the corresponding experimental value. However, the experimental value is within the standard deviation limits of the computational result. It is expected that increasing the sample size of the model would result in reducing the discrepancy to within the 10% range. However, for the benchmark calculations a computational run time of 12 hours or less was targeted and higher accuracy results were not obtained in the present analysis.

Thus, obtained results are in agreement with the available data. The observed modeling discrepancy is around 1%. The larger discrepancy, 6%, between experimental evaluations and computational results for the HTTR core with fully inserted control rods is due to ambiguity of available information regarding control rods and the core configuration.

3. Preliminary Configuration Adjustment Analysis

The HTTR configuration with fully withdrawn control rods was chosen as a prototype VHTR configuration (prismatic core case). The best agreement with experimental data was observed for that case. Table 2 summarizes basic reactor physics characteristics obtained for the prototype core.

Table 2: Basic Reactor Physics of the HTTR with Fully Withdrawn Control Rods.

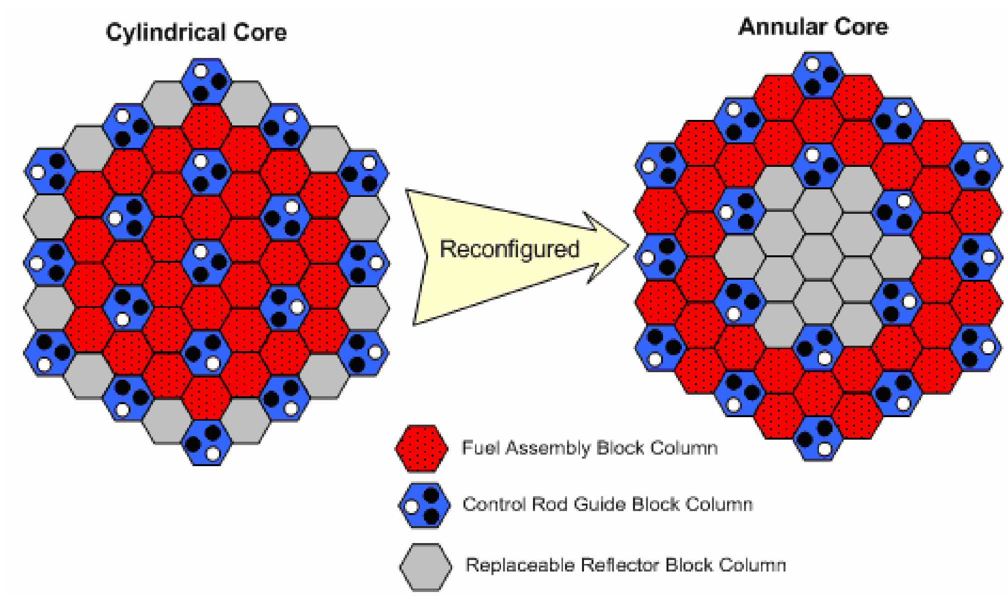
k_{eff}	Fission-Inducing Energy (eV)	System Mean Free Path (cm)	Fission Neutron Yield
1.1255 ± 0.0018	0.0846757 ± 0.0002343	2.72263 ± 0.00084	2.43846 ± 0.00001

It is proposed that through configuration adjustments, spectrum shifting can be achieved, with the end result of improving fissile properties of minor actinides. With that concept in mind, an analysis of the energy-dependent neutron flux in the core was performed.

For preliminary analysis purposes, the prismatic whole-core 3D model was adjusted from the original cylindrical core of the HTTR to that of an annular core. For simplification purposes, the process included changing the fuel in the core from a mixture of uranium enrichments (12 types) to just one enrichment throughout the entire core (8 wt%). To create the annular core, the model was reconfigured by replacing the fuel assembly block columns located in the inner region of the core with the replaceable reflector block columns in the outer region, and vice versa. An exact representation of the configuration adjustment is provided in Fig. 4.

The original cylindrical core was modified by changing the uranium enrichment to 8 wt% in order to analyze and compare data from both core arrangements. The cylindrical and annular cores were modeled so that energy distributions could be obtained for different regions of interest in the cores.

Figure 4: Vertical Cross-sectional View of VHTR/HTR10 Model (KENO 3D).

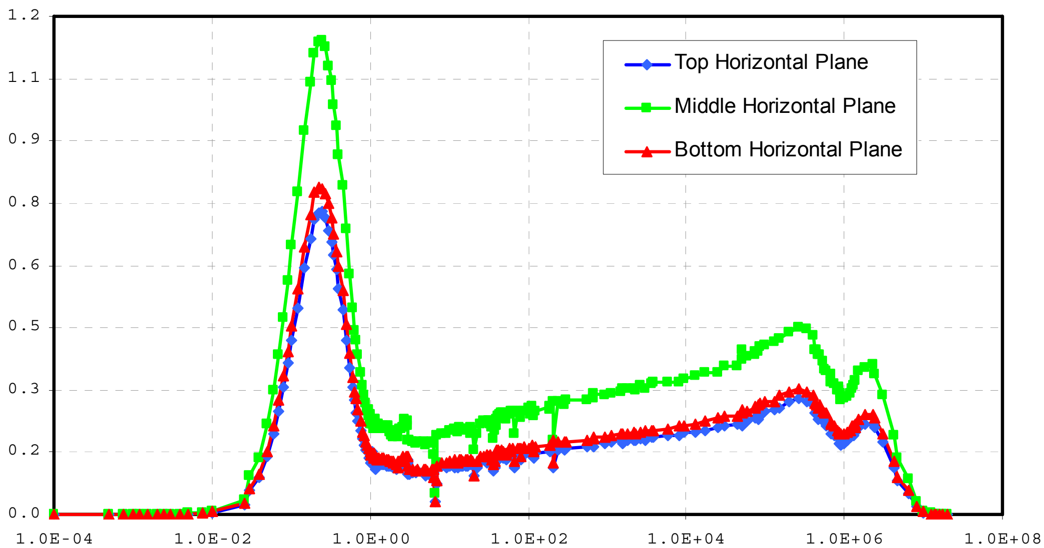


An evaluation of the neutron flux for all available positions in the annular core was performed. The average energy-dependent neutron flux obtained for the fuel compacts located in the top, middle, and bottom horizontal planes of the annular core configuration is provided in Fig. 5. Likewise, the fluxes for the inner and outer ring of fuel assembly columns are shown. As indicated by the flux profiles the highest flux is experienced in the middle horizontal plane of the outer fuel assembly columns.

Nuclear characteristics of minor actinides (MA) were examined over ENDFB 6.8, JENDL 3.3 and JEF 2.2 nuclear data libraries. The data were examined for ^{237}Np, ^{241}Am, ^{242m}Am, ^{243}Am, ^{242}Cm, ^{243}Cm, ^{244}Cm and ^{245}Cm; with ^{235}U and ^{238}U as reference nuclides. However, the detailed analysis of nuclear data files shows significant variations for minor actinides. These variations cause uncertainties that may result in error propagation and erroneous conclusions.

Besides data uncertainties, the enhanced involvement of minor actinides is further complicated by their low delayed neutron yields. The gross effect of this can be derived by benchmarking the primary data with experimental results to determine the contribution of each data set to the inconsistencies noted. The knowledge of the overall error propagation will help better prediction of nuclear characteristics from existing data.

Figure 5: Energy-Dependent Neutron Flux in the Fuel Compacts for the Annular Core Configuration.



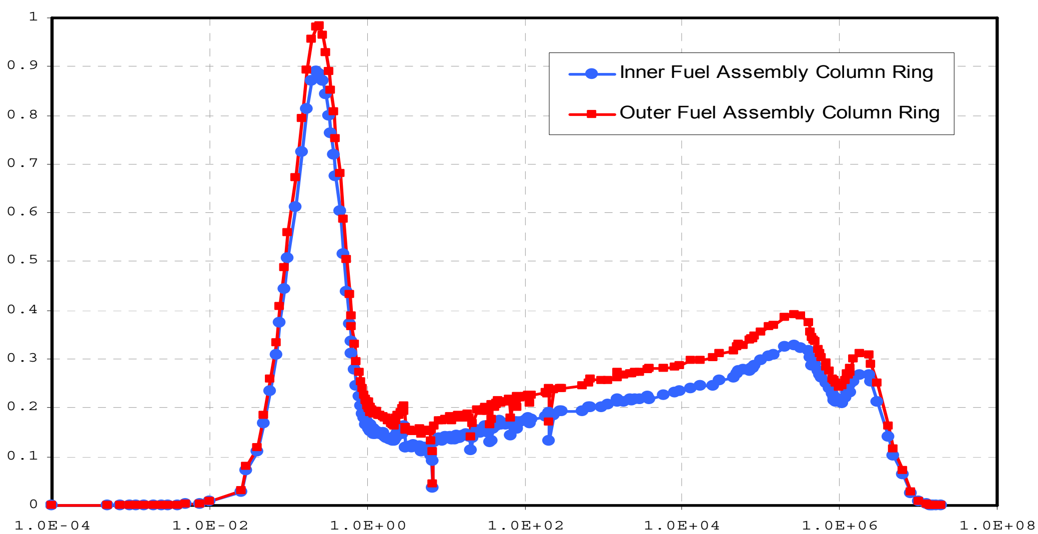
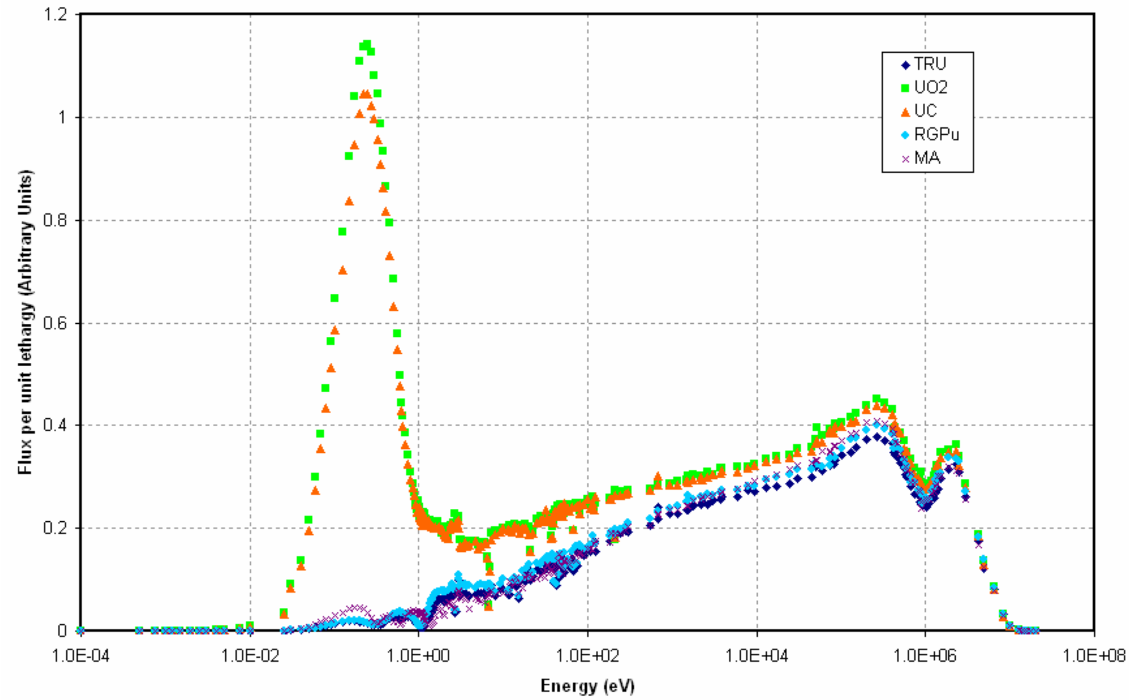


Figure 6 illustrates the anticipated core performance of the prototype small-scale VHTR with advanced actinide fuels. The observed behavior is consistent with nuclear characteristics of the considered compositions. Reactor cores with MAs require additional fissile material to assist criticality. Both enriched uranium or plutonium compositions can provide the required multiplication enhancement. According to the preliminary analysis, safety characteristics of all configurations are very similar to the reference core performance. Presence of higher actinides in the core should yield reduced reactivity swings during reactor operation and self-stabilization of compositions leading to a prolonged operation without refueling. The detailed analysis of the core performance during operation is in progress. The advanced actinide loadings are limited by heating rates and it is expected that full core loadings would require specialized design solutions.

Figure 6: Prototype Annual Core with Reference and Advanced Actinide Fuel Compositions.



4. Conclusions

The ultra-long life VHTR systems are developed and analyzed focusing on control, dynamics, safety, and proliferation-resistance during reactor lifetime long autonomous operation. The principal mechanism being envisioned to achieve ultra-long life systems is an enhanced involvement of self-generated fissile compositions based on spent LWR fuel to the energy generation process.

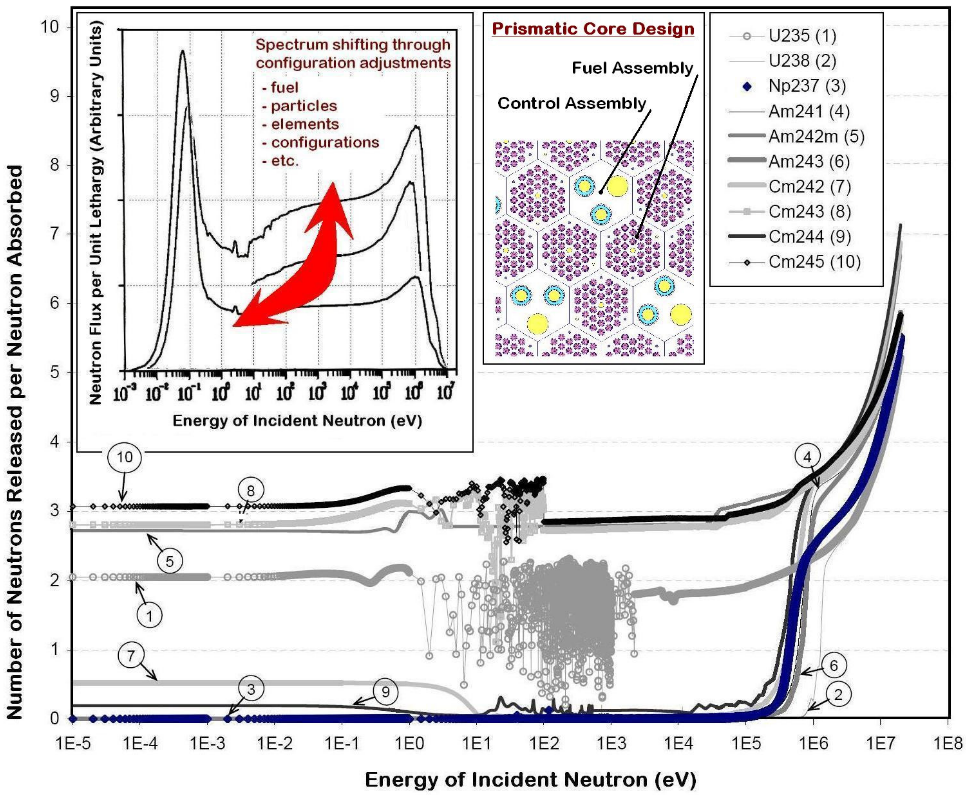
As illustrated in Fig. 7, depending on neutron spectra in the considered core configurations, neptunium, americium and curium may serve as burnable poisons or fuel materials contributing to small reactivity swings (self-stabilization) over prolonged irradiation periods yielding high levels of burn-up. Since pebble bed and prismatic core designs permit flexibility in component configuration, fuel utilization and management, it is possible to improve fissile properties of minor actinides by neutron spectrum shifting through configuration adjustments.

The main advantages of the resulting ultra-long life VHTR configurations are their inherent capabilities for utilization of minor actinides from spent LWR fuel, reduction of spent fuel flows and handling per unit of produced energy, and their potential for autonomous operation with minimized maintenance. Consequently, if widely deployed, the developed designs would allow reducing the long-term radiotoxicity and heat load of high-level waste sent to a geologic repository and enable recovery of the energy contained in spent fuel.

The project evaluates potential linkage and applications for Generation IV NGNP VHTRs in the AFCI Program. The developed ultra-long life VHTR configurations with advanced actinide fuels allow reduction of spent fuel volume, separation of long-lived, high-level waste nuclides (minor actinides) and their utilization, and recovery of spent fuel's valuable energy.

This research effort enhances capabilities of the Generation IV VHTR and transforms it to a technology that can deliver electricity, hydrogen, and assist in spent fuel treatment while being inherently safe, environmentally friendly, and proliferation resistant. The technology is also going to be cost effective because of actinide recycle, high burn-up and reactor lifetime long autonomous operation expanding deployment to developing countries and remote areas

Figure 7: Spectrum shifting capabilities and neutronics performance of transuranic nuclides



Acknowledgements

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