A Direct Comparison of High-Order and Low-Order Neutronics Calculations of the 165 MW_{th} Xe-100 Reactor

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INTRODUCTION

The Xe-100 is a helium-cooled graphite-moderated high-temperature pebble bed reactor (HTGR) designed by X-energy, which is a nuclear reactor and fuel design engineering company located in Greenbelt Maryland. As one of the generation IV reactor designs, thanks to the TRISO-coated fuel employed, the Xe-100 has passive safety features that can prevent unallowable contamination of the land and eliminate the need to evacuate or displace the public under any circumstances [1]. Besides the intrinsic safety, the Xe-100 also has numerous other advantages, including

- the pebble fuel form allows online refueling scheme;
- low excess reactivity is needed because of the continuous refueling scheme;
- high outlet coolant temperature that leads to high electricity generation efficiency and high-temperature industrial process heat;
- the capability of functioning in a load-following mode;

Viewing all these technical merits of the Xe-100, X-energy was awarded $80 million by the Department of Energy's Advanced Reactor Demonstration Program (ARDP) as the initial funding to build a commercial-scale Xe-100 advanced reactor than can be operational by 2027.

Several HTGR plants have been constructed and operated worldwide to demonstrate the superior performance of this type of reactors, including Dragon (1966-1975, UK), Peach Bottom (1966-1974, USA), AVR (1967-1988, Germany), Fort St. Vrain (1967-1988, USA), and THTR (1986-1989, Germany), etc. The prismatic-type HTTR in Japan and the pebble-bed type HTR-10 in China are currently the only two HTGRs in the world that are functioning, and studies considering these state-of-the-art HTGR designs never stopped. For example, Tang and coworkers recently published their work analyzing the pebble burnup profile in HTR-10 [2].

More detailed modeling efforts considering the Xe-100 design are also required to further enhance the reactor safety and to improve its economic efficiency. Therefore, in this paper, we built a high-order Monte Carlo neutronics model of the Xe-100 reactor core. A preliminary neutronics study of the 165 MWth Xe-100 reactor is performed to achieve neutronics characteristics of the core with a code-to-code verification of the calculations results obtained by using both the lower-order VSOP-A diffusion code [3] and the higher-order Serpent Monte Carlo code [4].

COMPUTTATIONAL MODELS

Low-Order Diffusion Model

Neutronic calculations a 165 MWth Xe-100 reactor were performed [1] by using the system of design diffusion code VSOP-A developed at X-energy [3]. A schematic of the reactor is shown in Fig. 1, and the VSOP-A model of the reactor core is shown in Fig. 2.

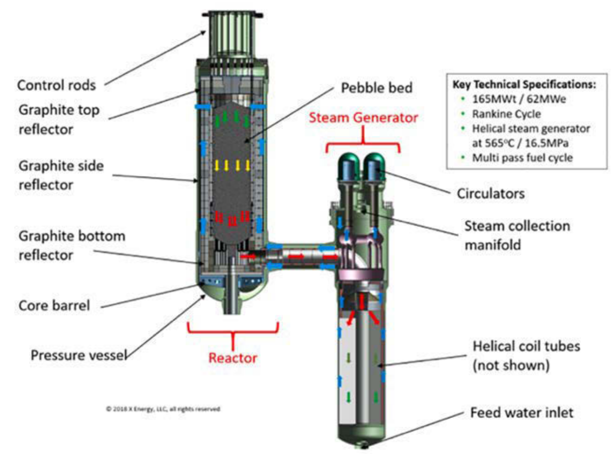

Fig. 1. Schematic of the 165 MWth Xe-100 reactor [1].

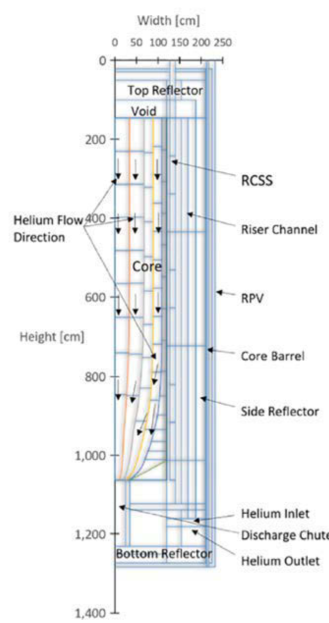

Fig. 2. VSOP-A model of the Xe-100 reactor core [1].

TABLE I. Geometric and fuel specifications of the Xe-100 design [1].

Reactor geometry		Fuel pebble		TRISO coated particles	
RPV diameter	4.88 m	Pebble diameter	60 mm	Kernel diameter	0.425 mm
Core diameter	2.4 m	U loading per pebble	7 g	TRISO per pebble	~19,000
Core height	8.93 m	Enrichment level	15.5 wt%	Coating materials	C/PyC/SiC/PyC
Chute diameter	0.5 m	Pebbles in the core	~220,000 [5]	Layer thickness	100/40/35/40 μm

The ENDF/B-VII library was employed by VSOP to generate neutron cross sections, and the graphite thermal neutron scattering cross sections were specified. As VSOP is capable of performing both thermal-hydraulic and neutronic calculations, the neutron cross sections were generated on the fly as the temperatures changed. Numerous neutronics characteristics of 165 MWth Xe-100 were investigated, including control rod worth, steady-state fast and thermal neutron flux distributions, temperature reactivity coefficients, isotope changes through depletions, etc. The VSOP-A results obtained suggested that the core design fulfilled all the design parameters and the operating envelope [1].

High-Order Monte Carlo Model

The geometry and fuel specifications employed for the construction of the 165 MWth Xe-100 reactor are summarized in TABLE I. Similar to the VSOP model, the ENDF/B-VII.0 library was employed and the graphite thermal neutron scattering cross sections were specified. A constant fuel temperature of 900K and a constant moderator temperature of 600K were assumed considering the neutron cross section generation. The fuel kernels were modeled as $UC_{0.5}O_{1.5}$ with a ^{235}U enrichment of 15.5 wt.% and we modeled 19,542 identical TRISO fuel particles in each fuel pebble such that the uranium loading per pebble was 7 grams. The TRISO particles were randomly distributed in the center part of each fuel pebble by leaving an outer fuel-free zone with a thickness of 5 mm, as shown in Fig. 3 [1].

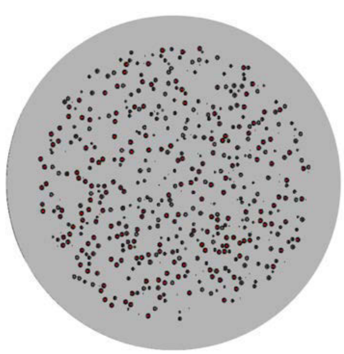

Fig. 3. Cross-sectional view of a fuel pebble with randomly distributed TRISO particles.

According to the specification of Ref. [5], we modeled 219,503 fuel pebbles, and considered all the fuel pebbles to have the same TRISO distribution for simplicity. In this preliminary Serpent model, we assumed that the fuel pebbles were densely packed in the core and modeled the pebbles by repeating the Hexagonal Closest Packing (HCP) unit cells, as shown in Fig. 4.

Control rod borings are located inside the reflector at around 10 cm away from the active core. Two types of control rods (CR) were modeled, namely the Reactivity Control System (RCS) with a maximum insertion length of 660 cm and Reserve Shutdown System (RSS) with a maximum insertion length of 860 cm. Both types of CR have a diameter of 13 cm and an active length of 660 cm. The active part of the CR consists of annular B_4C compacts (8 mm thickness) stacked in Incoloy-800H [7] canisters, which have an inner radius of 41.5 mm, an inner wall thickness of 0.5 mm and an outer wall thickness of 2.5 mm. Fig. 5 shows the cross-sectional views of the preliminary Serpent model and the locations of the 18 CR (9 for RCS and 9 for RSS).

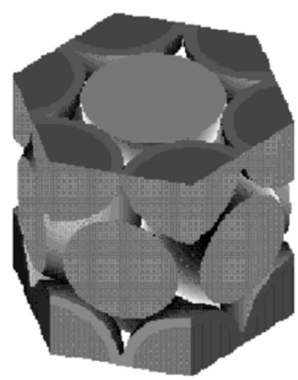

Fig. 4. HCP unit cell of the fuel pebbles [6].

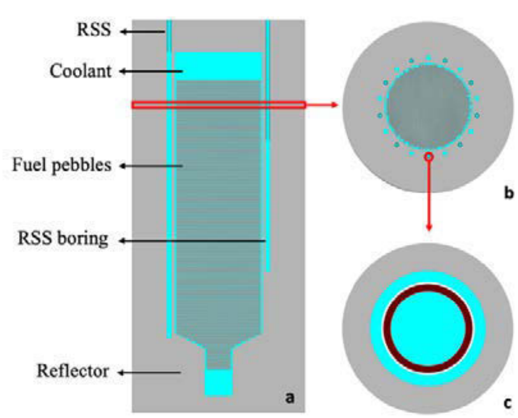

Fig. 5. (a) Vertical, (b) horizontal cross-sectional views of the Serpent model, and (c) a zoomed view of the CR.

We performed steady-state neutronics calculations by using one million realizations per cycle and five hundred active cycles (5×10^8 active neutron histories in total). The uncertainties associated with the calculated k_{eff} were smaller than 10 pcm, and the calculations were finished within 13 hours by using 40 processor cores. The low uncertainties and the reasonable computational expense demonstrated the feasibility of performing depletion and reactivity temperature coefficients calculations by using this Serpent Xe-100 model.

RESULTS

Several calculation results based on the preliminary Serpent model of the 165 MWth Xe-100 design are obtained. The fresh-core neutron spectrum tallied with 200 equal-lethargy groups for the Xe-100 core is shown in Fig. 6 in comparison with that in the representative HTGR design – the GA's 350 MWth MHTGR [8]. The very similar spectra in both cores demonstrated the current Serpent model of the Xe-100 design to be reasonable.

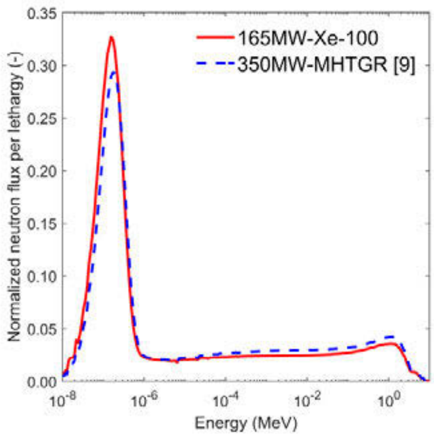

Fig. 6. Neutron spectrum in the core of Xe-100.

The core averaged radial neutron flux distributions calculated by both Serpent and VSOP are compared in Fig. 7. The flux are structured into 4 groups [1]. The maximum normalization is performed for the flux plots. The fast flux (E > 0.1 MeV) had a good agreement, while the radial location of the peak of the thermal flux (E < 1.86 eV) had a slight discrepancy of about 5 cm.

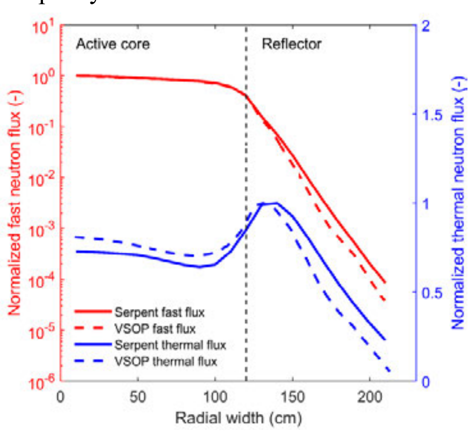

Fig. 7. Radial flux distribution in the core of Xe-100.

We calculated the integral CR worth as the difference between the k_{eff} of the core with all CR withdrawn from the reactor and that with CR inserted with different length. The integral CR worth calculated by both codes are compared in Fig. 8. The worth of the RSS was minor in the overlap region with RCS because the former was calculated by considering that RCS was completely inserted. The integral CR worth calculated by both codes had a similar trend, and the maximum difference was on the order of 3400 pcm. This difference is acceptable considering that the Serpent model is still in the preliminary stage.

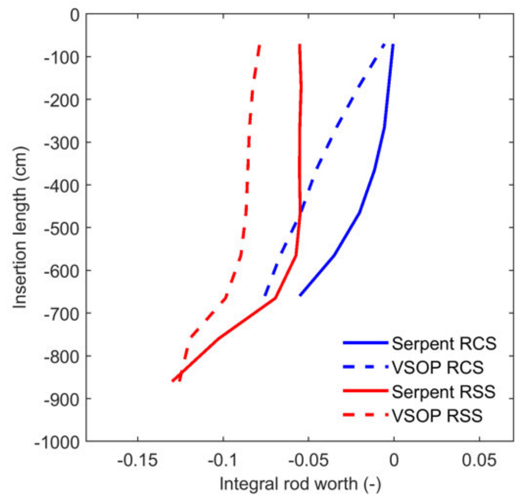

Fig. 8. Integral control rod worth of Xe-100.

We then performed a whole core depletion calculation up to the average burnup of the Xe-100 design, 165 MWd/kgHM [1]. The reactivity changes as a function of the burnup from the depletion calculation is shown in Fig. 9. It should be noted that the plotted reactivity curve does not reflect the actual reactivity changes of the Xe-100 fuel cycle. The excess reactivity envisioned in the Xe-100 core should be much small and the reactivity swing is much smooth thanks to the continuous refueling scheme.

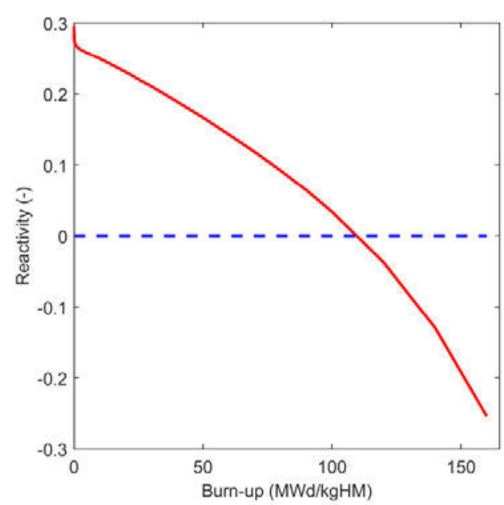

Fig. 9. Reactivity as a function of burnup.

The depletion of ^{235}U and the buildup of ^{239}Pu in the Xe-100 core, calculated with both Serpent and VSOP, are compared in Fig. 10. Both the depletion of ^{235}U and the buildup of ^{239}Pu calculated by VSOP were around two times faster than that from the Serpent model. This discrepancy may be explained by the harder neutron spectrum considered in the VSOP model, but a more in-depth investigation is needed for a more accurate explanation.

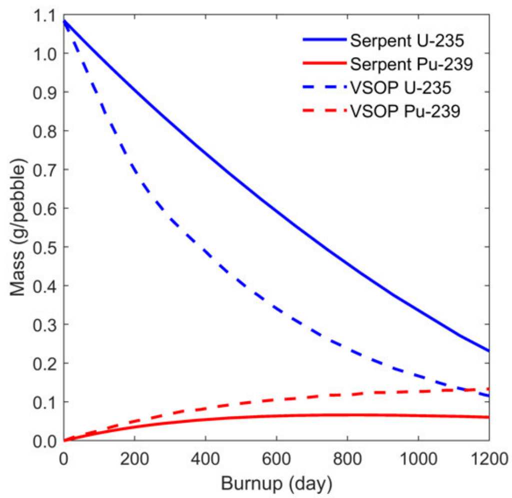

Fig. 10. The ^{235}U and ^{239}Pu changes in the Xe-100 core.

Two types of Reactivity Temperature Coefficients (RTC) of the Xe-100 core, namely the Doppler Coefficients and the Moderator Temperature Coefficients, were approximately evaluated with the Serpent model by considering that:

$$RTC(T) = \frac{k_{eff}(T+50℃) - k_{eff}(T-50℃)}{100℃} \quad (1)$$

The Doppler Coefficients were calculated by fixing the moderator temperature at 600K and the MTCs were calculated by fixing the fuel temperature at 900K. A comparison between the RTCs obtained with both Serpent and VSOP codes is shown in Fig. 11.

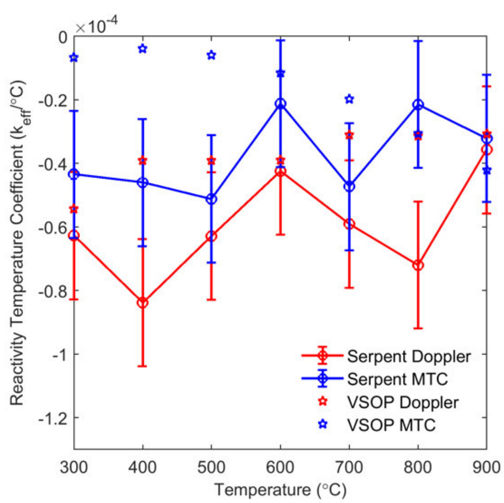

Fig. 11. Doppler and MTC of the Xe-100 core.

The results obtained generally had an acceptable agreement. Both types of RTCs were negative at all the temperature investigated and the Doppler coefficients were slightly more negative than the MTCs. The differences in the RTCs obtained with both codes may be caused by the different assumptions employed during the calculations.

CONCLUSIONS AND FUTURE WORK

In this study we built a preliminary Serpent model of the X-energy's 165 MWth Xe-100 design. In order to evaluate the performance of our Serpent model under development, several characteristics of the Xe-100 design were calculated with the preliminary Serpent model and compared with those obtained with the VSOP model. The characteristics investigated included the radial neutron flux distribution, the integral control rod worth, ^{235}U depletion and ^{239}Pu buildup throughout the fuel cycle, and the reactivity temperature coefficients. These comparative studies indicated the accurate modeling of X-100 core using Serpent.

For the further work, we will extend our investigations to more characteristics of the Xe-100 design. We will also further refine the preliminary Serpent model of the 165 MWth Xe-100 design by adding more details, such as the coolant channels. Moreover, instead of the HCP packing structure employed in this study, the locations of each fuel pebble will be determined by using the discrete element method (DEM) [9], and all the pebbles will be modeled at their designated locations.

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