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Preliminary Concept Design of Sodium-Cooled Radial Fuel Shuffling Traveling Wave Reactor

Wenxi Tian[1], Meiyin Zheng[1], Xiao Chu, Dalin Zhang[1], Guanghui Su and Suizheng Qiu
[1]School of Nuclear Science and Technology, Xi'an Jiaotong University, Xi'an 710049, China

Abstract

The concept of traveling wave reactor (TWR) has been investigated for several decades and has been applied to different kinds of reactors. Radial fuel shuffling TWR is a new concept, which has been put forward for only a few years by Terra Power LCC. In the present paper, a sodium-cooled radial fuel shuffling TWR is preliminarily designed. To perform neutronic and burn-up investigations, a MCNP-ORIGEN coupled code system, called MCORE, is used. The comparison between calculation results of MCORE and benchmark values showed the calculation ability of MCORE. The calculation results of radial fuel shuffling TWR show that the asymptotic k_{eff} parabolically varies with the shuffling period, while the burn-up increases linearly with shuffling period. The power peak shifts from the core inside to the core outside. To reduce the power peak, shuffling period 450 days is recognized as the best design. The asymptotic is 1.020 and the average burn-up is about 156.0 MWd/kg-HM.

Introduction

In ICENES 1996, Teller et al. [1] proposed an automated self-controlled nuclear fission reactor concept, in which a nuclear breeding/burning was ignited and propagated slowly in the core axial direction. Natural uranium and thorium fuel can be used in this type of reactor, and no fuel enrichment and reprocessing are needed. Theoretical investigations of this new concept of reactor were performed by Van Dam [2], Seifritz [3], and Chen et al. [4, 5], which provided fundamental insight into this new reactor concept. Intensive numerical studies were made by Sekimoto et al. [6]. They solved the multi-group diffusion and burn-up equations numerically and obtained a quasi-asymptotic solution, based on which they came up with the CANDLE burn-up strategy.

In recent years, Terra Power LCC proposed two prototype reactors, which were quite different from the exiting TWR concept. In these two reactors, the breeding/burning wave does not move from one end of the reactor to the other but gradually from the inside out. Theoretical and numerical studies of this new concept were performed by Chen et al. [7] and Zhang et al. [8]. Chen et al. found that the inward fuel drifting has a better breeding utilization than the outward one. Zhang et al. theoretically and numerically studied TWR based on European Sodium-cooled Fast Reactor (ESFR). Radial fuel shuffling TWR overcomes some drawbacks of axial TWR, such as cladding integrity, accumulated fission product gas and large power peaking factor.

In this paper, a preliminary concept of sodium-cooled radial fuel shuffling TWR is designed. MCORE [9] is applied to perform burn-up calculation and stable power distribution is obtained. The results show that asymptotic k_{eff} parabolically varies with the fuel shuffling period, while the burn-up increase linearly. The power peak shifts from the core outside to the core centre. To reduce the

power peak, fuel shuffling period 450 days is recognized as the best design. The asymptotic k_{eff} is 1.020 and the burn-up is up to about 156.0 MWD/kg-HM.

1. MCORE burn-up code

For a TWR problem, the neutron diffusion equation is coupled with burn-up equations. In this paper, a MCNP and ORIGEN coupled code system, named MCORE, is used to solve this problem.

MCORE is a FORTRAN computer code, which provides full capabilities of the Monte Carlo code MCNP and the versatile nuclides depletion and decay code ORIGEN. The code makes use of the tally information of MCNP to get power distributions, neutron fluxes and nuclides. MCNP and ORIGEN are coupled by data processing and linking subroutines. The flow diagram of MCORE is shown in Fig. 1. MCORE has several merits. (1) MCORE uses a so-called "modified predictor corrector" approach, in which MCNP executes at the beginning and middle of the internal time step. This approach can enlarge the time step and ensure enough calculation accuracy. (2) Total atom density changes in active cells are considered to ensure calculation precision for high burn-up problem. (3) The user should only prepare the initial MCNP input file, the initial nuclides density file and calculation scheme file, which makes it easy for new users who know nothing about ORIGEN to use it. (4) MCORE can be used to simulate fuel shuffling.

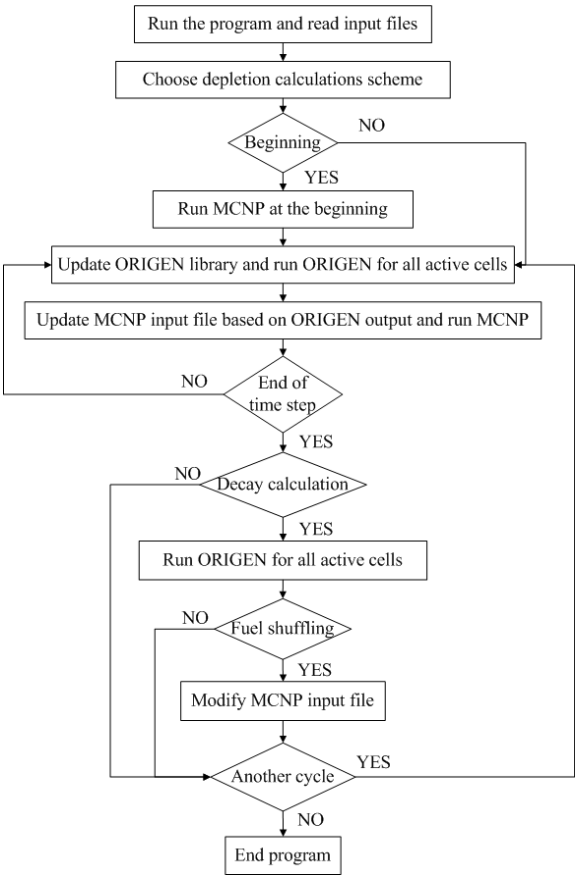


Fig. 1 Flow diagram of MCORE

To evaluate the reliability and accuracy of MCORE, a VVER-1000 LEU assembly benchmark and fast reactor reported results are compared with MCORE results. For LEU assembly, the absolute error from the Benchmark Mean (BM) values for k_∞ is found to be within 800 pcm and the relative deviation from the BM values for isotopic composition of considered isotopes is remarked to be within 5% at the end of burn-up. For the fast reactor, the results obtained by MCORE are in the range of reported results. In general, MCORE results show good agreement with the reported results, which mean that MCORE can perform burn-up calculation for pressurized water reactor (PWR) and sodium cooled fast reactor (SFR).

2. Core design and radial fuel shuffling strategy

2.1 Core parameters and arrangement

Zhang et al. [8] dealt with radial fuel shuffling TWR based on the core design of the ESFR, in which the total thermal power was 3600 MW. Following their investigation, in this work, a 2000 MW sodium cooled radial fuel shuffling TWR is designed. The fuel, coolant and steel volume fraction are 52.36%, 27.60% and 20.04%, respectively. The core layout is shown in Fig. 2, which consists of 19 control and shutdown subassemblies (CR&SR), 270 fuel subassemblies (FA) and about three layers of reflectors. The height of active core is 1.0 m, the radius of active core is about 1.86 m and the main parameter is shown in Table 1. Natural uranium is used as fresh fuel material.

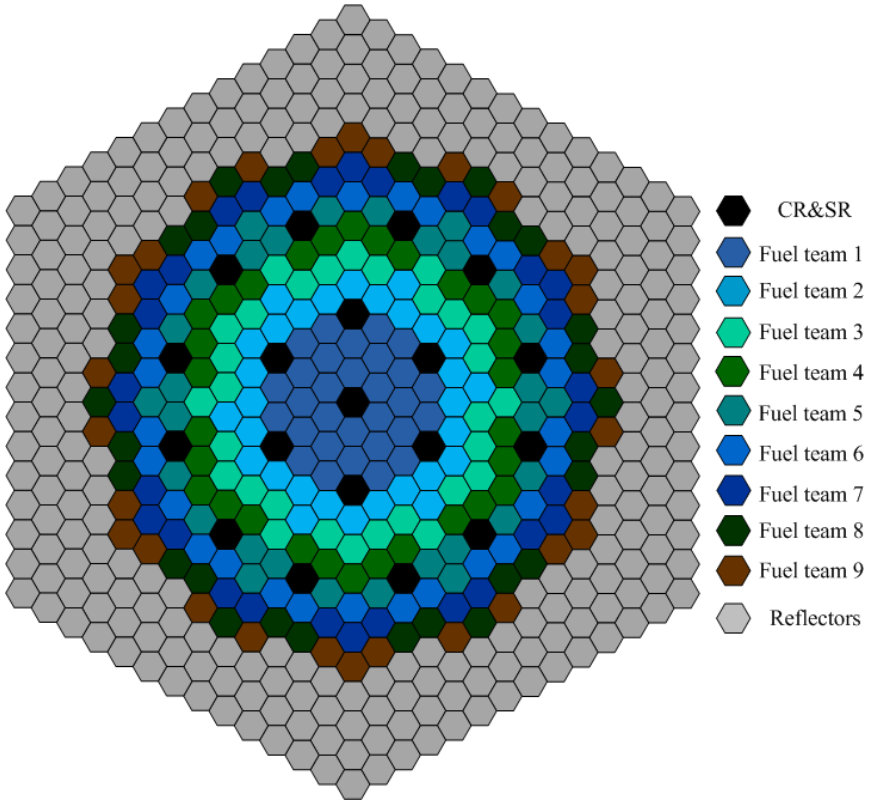


Fig. 2 Core arrangement

Table 1 Core design parameters

Total thermal power (MW)	2000
Number of fuel subassemblies	270
Number of control and shutdown subassemblies	19
Active core height (m)	1.0
Volume fraction of fuel (%)	52.36
Volume fraction of coolant (%)	27.60
Volume fraction of steel (%)	20.04
Fuel density (g/cm^3)	19.1
Coolant density (g/cm^3)	0.83
Steel density (g/cm^3)	7.7

Fuel assembly pitch is 208.3 mm. Total fuel element height is 2550 mm. The height of upper blanket and lower blanket are 150 mm and 300 mm, respectively. Gas plenum is arranged at the upper and lower of the fuel element to keep fission product gas.

2.2 Radial fuel shuffling strategy

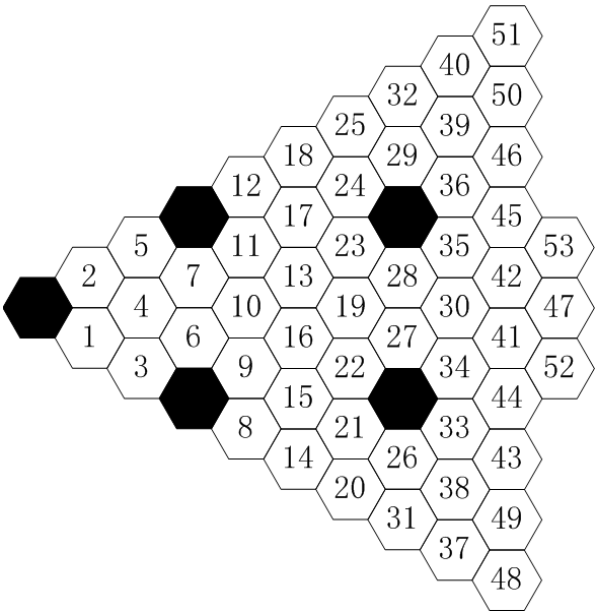


Fig. 3 Subassembly number of the 1/6 core

In [7], the fuel shuffling was simulated by a continuous model. In [8], the burn-up and neutronic calculations were performed for a 2-D discrete model. In that paper, the fuel subassemblies were divided into several groups, and every group has the same total number of subassemblies. In 2-D simulation, the active core was divided into several homocentric annular regions with equal ring area in radial direction. The fuel radially moved stepwise from one ring to the next adjacent ring at the same

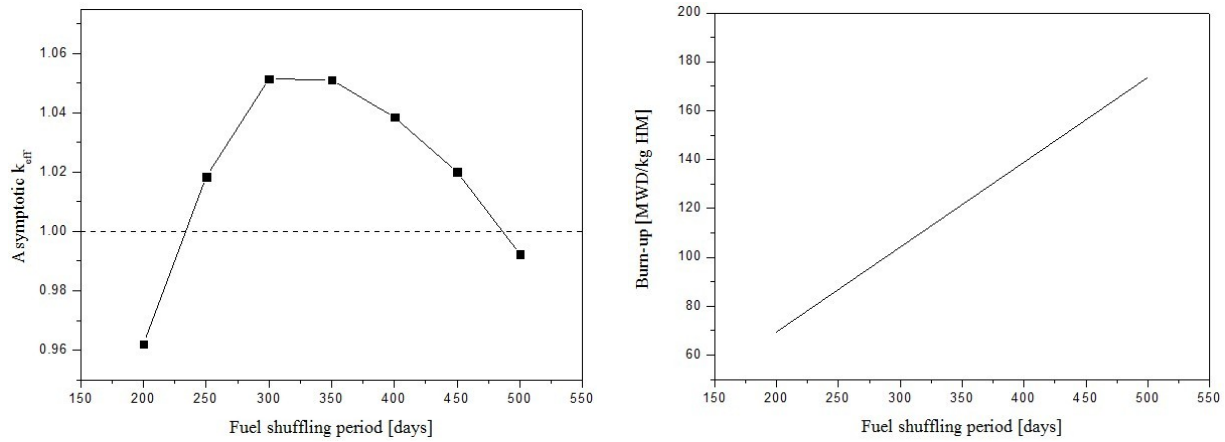
time inwards. Fresh fuel was charged into the outermost ring and the spent fuel was discharged from the innermost ring.

In this paper, the burn-up calculations are performed with a 3-D model. The fuel subassemblies are divided into 9 groups and every group consists of 30 subassemblies. Every subassembly of the same group almost has the same distance to the core centre. As theoretical studies [7] show that the inward fuel shuffling is better than the outward fuel shuffling in fuel utilization, inward fuel shuffling strategy is directly applied in this paper. The spent fuel is discharged from the core centre, and fresh fuel is charged from the outer core. Subassemblies of the same group are moved to the next group inwards. Subassembly numeration of the 1/6 core is shown in Fig. 3. CR&SR (black) are not considered in the calculation.

3. Results and Discussion

According to the radial fuel shuffling strategy and the calculation scheme, it can be easily deduced that the reactor will tend to an asymptotic state after certain fuel shuffling steps, where the k_{eff}, power distribution and nuclide number density distributions will become constant. After the core structure, total thermal power, subassembly group and the fresh fuel material being fixed, the asymptotic state will only depends on the fuel shuffling period.

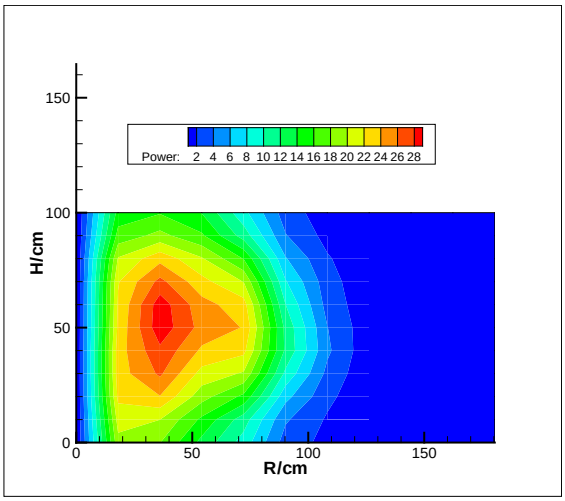
Fuel shuffling period 200, 250, 300, 350, 400, 450, 500 days are chosen for calculation. The asymptotic k_{eff} and average burn-up of these fuel shuffling periods are shown in Fig. 4. As shown in Fig. 4(a) that not all the fuel shuffling periods satisfy the core critical condition. If the fuel shuffling period is too short or too long, the core will become subcritical, which is easy to be deduced. If the fuel shuffling period is too short, some ^{239}Pu, transformed from ^{238}U, will be discharged and not be fully used. While if the fuel shuffling period is too long, ^{238}U will be exhausted. As shown in Fig. 4 that the asymptotic k_{eff} parabolically varies with the fuel shuffling steps, while average burn-up increases linearly. This feature indicates that the asymptotic state can be controlled by fuel shuffling period, and the average burn-up can be reduced by reducing the fuel shuffling period.



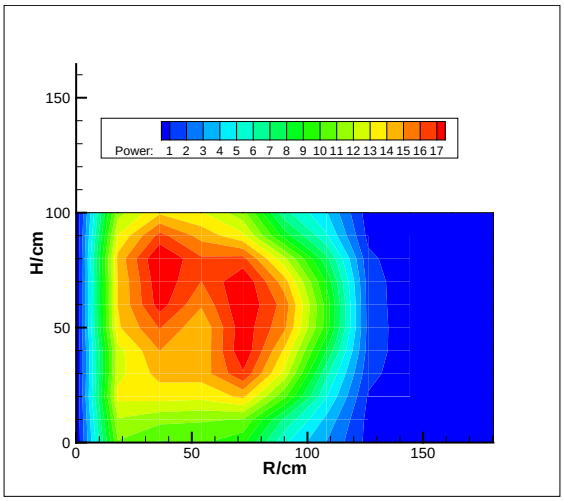
(a) Asymptotic k_{eff} (b) Average burn-up

Fig 4 Asymptotic k_{eff} and average burn-up as a function of fuel shuffling period

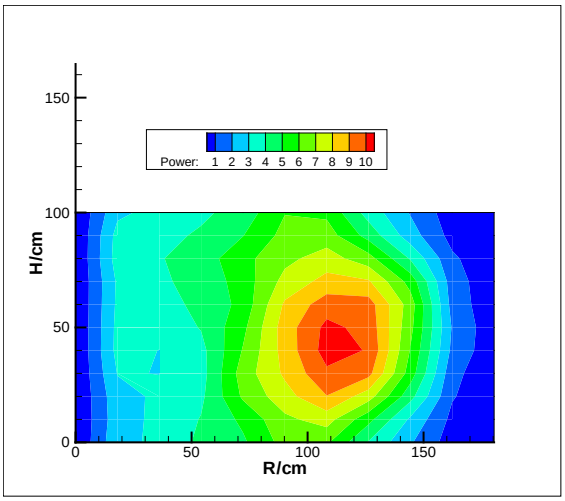
Power distributions of fuel shuffling period 250, 300, 350, 400 and 450 days are shown in Fig. 5. It should be mentioned that in the centre of the core is CR&SR. It can be found that the power peak drifts from the inner core to the outer core with the increasing of fuel shuffling period, which is related to the shuffling strategy. When the fuel shuffling period is short, ^{239}Pu, transformed form ^{238}U, will burn for many shuffling steps before been discharged, so the power peak is near the core centre. When the fuel shuffling period is long, ^{239}Pu will burn for a few shuffling steps before been discharged, so the power peak is near the core centre. As shown in Fig. 5(e), the minimum power peak factor is up to almost 9.5, which is too large. Large power peak factor can be solved by scattered shuffling strategy, which will be shown in our later investigations. To reduce the power peak factor, fuel shuffling period 450 days is recognized as the best design. The asymptotic k_{eff} is 1.020 and the average burn-up is up to about 156.0 MWd/kg-HM.



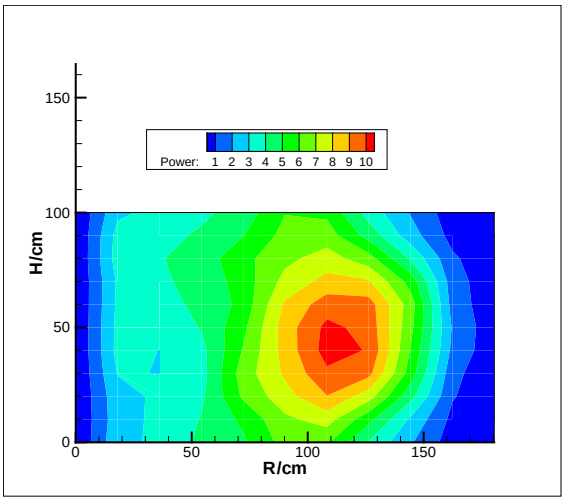
(a) Fuel shuffling period 250 days



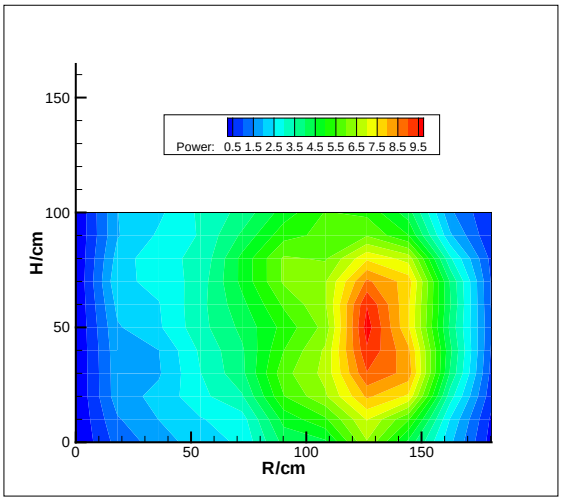
(b) Fuel shuffling period 300 days



(c) Fuel shuffling period 350 days



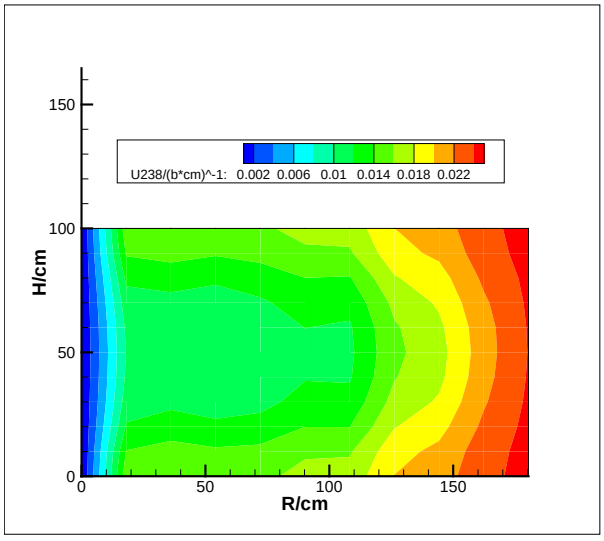
(d) Fuel shuffling period 400 days



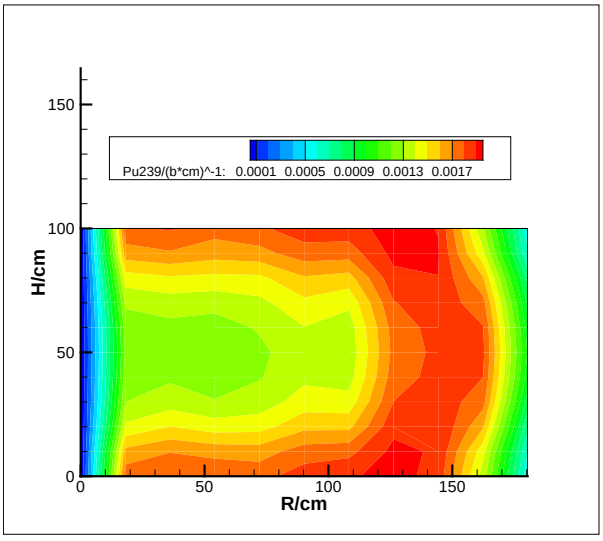
(e) Fuel shuffling period 450 days

Fig. 5 Power distribution of different fuel shuffling periods

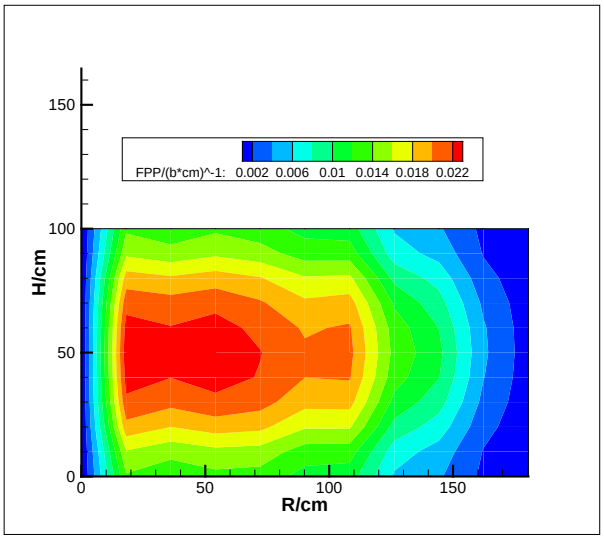
Fig. 6 shows the atom density distributions of ^{238}U, ^{239}Pu and fission product (FPP) with the fuel shuffling period of 450 days. As shown in Fig. 6(a) that, the fertile fuel decreases from the outer core to the inner core monotonously, since most of ^{238}U is transformed to ^{239}Pu during burn-up. Since the neutron flux in the core central region is higher, ^{238}U decreases faster in the core centre. From Fig. 6(b), it can be found that fissile fuel increases from the outer core because of breeding effect of ^{238}U, then decreases slowly due to the burning effect. For the same reason, ^{239}Pu changes quicker in the core central region. As shown in Fig. 6(c) that FPP increases monotonously from the outer core to the inner core due to its accumulation during burn-up. Main parameters of the best design are shown in Table 2.



(a) ^{238}U



(b) ^{239}Pu



(c) FPP

Fig 6 Atom density distributions of fertile and fissile nuclides

Table 2 Main parameters of fuel shuffling period 450 days

k_{eff}	1.020
Power peak factor	9.4
Average burn-up (MWD/kg-HM)	156.0

4. Conclusion

In this paper, a 2000MWt sodium cooled TWR is designed. To perform neutronic and burn-up calculation, MCORE burn-up code is applied. As inward fuel shuffling strategy shows better fuel utilization from theoretical investigation, the inward fuel shuffling strategy is adopted. The burn-up calculations are performed for a 3-D model. Several interesting results are obtained: (1) the asymptotic k_{eff} parabolically varies with the shuffling period, while the burn-up increase linearly with shuffling period; (2) the power peak drifts from the inner core to the outer core with the increasing of fuel shuffling period; (3) fuel shuffling period 450 days is recognized as the best design, the asymptotic k_{eff} is 1.020 and the average burn-up is up to 156.0 MWd/kg-HM.

5. References

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