Study of burnup process in the VVER-1200 reactor with plutonium refueling options

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Abstract. This paper aims to investigate and compare the burnup processes of the VVER-1200 reactor fueled with reactor-grade and weapon-grade plutonium mixed with depleted uranium (MOX) through simulation with the GETERA code. The burnup calculation was performed using a unit fuel cell model, taking into account the center hole of the fuel pellet and the gas gap between the fuel and the cladding. The number of reloads for all cases was calculated. The infinite multiplication factor versus burnup graphs, as well as the behaviors of isotopes under all conditions, have been obtained and studied. The graphs of the infinite multiplication factor versus burnup and the behaviors of isotopes for all cases were obtained and analyzed. The results showed closing the VVER-1200 fuel cycle can be achieved by using MOX fuel.

1 Introduction

The only naturally occurring isotope that can fission using thermal neutrons is uranium-235, which makes up 0.71% of natural uranium. However, transmutation-decay chains result in the production of three more fissile (fissionable by thermal neutrons) isotopes of significant importance as nuclear reactor fuel. Fertile isotopes are those that can undergo neutron transmutation and decay to become fissile isotopes. In the transmutation-decay chain starting with the fertile isotope 238U, ^{239}Pu and ^{241}Pu are the byproducts, and ^{233}U is the byproduct of the chain starting with the fertile isotope 232Th [1].

One of the most essential and fundamental aspects of nuclear power is that, rather than utilizing prepared nuclear fuel once and then disposing of it, most of it can be recycled, thereby closing the fuel cycle [2]. The current method is to separate the plutonium and recycle it as mixed oxide (MOX) fuel, which is mixed with depleted uranium [3-4].

To achieve a closed fuel cycle, analyzing the performance of reactor-grade plutonium in nuclear reactors is an important area of research [5]. In addition, the denuclearization of the world is of utmost importance to have prospered and peaceful world.[6] Deploying weapon-grade plutonium from the dismantled nuclear warheads to the nuclear reactors is beneficial [7].

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The variations in composition brought on by fuel burnup and how these are compensated for over the course of a nuclear reactor's lifespan define the long-term changes in its properties. The effectiveness of using fuel to generate electricity has a significant impact on nuclear power's economics, which in turn is impacted by these long-term modifications brought on by fuel burnup. In this work we describe the changes in fuel composition that take place in an operating VVER-1200 reactor and their effects of samarium and xenon fission products with large thermal neutron cross sections, the conversion of fertile material to fissionable material by neutron transmutation, and the effects of using plutonium from spent fuel and weapons surplus as fuel.

2 VVER-1200 Reactor core and fuel assemblies

There are 163 fuel assemblies in the reactor core. Reactor power is controlled by means of the 121 control rods of the control and protection system, by burnable neutron absorber in the fuel rods, and by change of boric acid concentration in the primary circuit water. Fuel assemblies with hexagonal shapes are employed in the VVER-1200 design. 312 of the 331 rods in the VVER-1200 reactor assembly are fuel rods, with the remaining rods serving as guide tubes for the control rod and central tube. As integrated burnable absorber (IBA) rods, 12 rods are homogenized with UO_2 and Gd_2O_3. Figure 1 shows a horizontal cross-sectional view of the reference assembly and a cell inside that assembly. Table1 lists the variables taken into account when modeling the reference assembly.

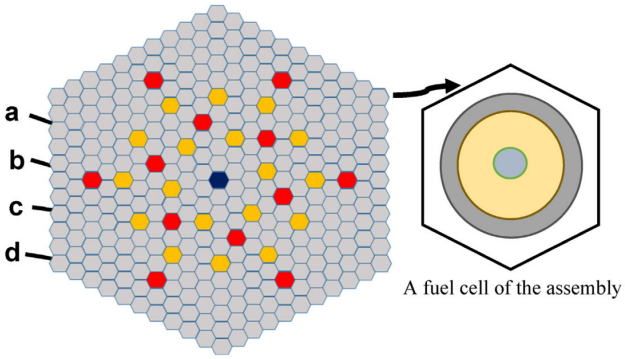

Fig. 1. Cross section of reference fuel assembly for VVER-1200 reactor: (a) central tube; (b) guide tubes for control rod; (c) IBA fuel rod (3.6%^{235}U 4% Gd_2O_3); (d) fuel rod (4.95% enriched UO_2) [8].

Table 1. Design parameters considered for the reference VVER-1200 fuel assembly [8-9].

Characteristics	Unit	Value
Diameter of the fuel rod/Pin pitch	mm	9.1/12.75
Diameter of the pellet/internal hole	mm	7.6/1.2
The thickness of the cladding	mm	0.685
Average core power density	kW/l	108.5
The pressure of the gas in the gap	MPa	2-2.45
Fuel temperature	K	873.0
Non-fuel temperature	K	573.0
235U enrichment in fuel rods	wt%	4.95
Moderator		Light water

3 Calculation method

In this paper, we see plutonium refueling options for the VVER-1200 reactor in several sets of variants (see Table 2). We analyze the burnup process, draw graphs for dependencies of Kinf on burnup and concentration change of several important isotopes e.g., ^{235}U, ^{238}U, ^{239}Pu, ^{135}Xe, and ^{149}Sm in traditional uranium fuel case, ^{240}Pu and ^{241}Pu in the case of plutonium fuel through the whole burn up time. Initially, we analyze the change in Kinf and concentrations through burnup. Then we move to investigate plutonium refueling options in which four variants analyze plutonium mixture with depleted uranium (enrichment is 0.5%). In all variants, weapon-grade plutonium and reactor-grade plutonium cases are investigated [10].

Table 2. Fuel content for each variant.

Variants	Fuel
v1	Traditional fuel
v10	4% WG(95%Pu239, 5%Pu240) PuO_2
v12	4% RG(83%Pu239, 17%Pu240) PuO_2
v13	8% RG(70%Pu239, 30%Pu240) PuO_2
v14	5% WG(95%Pu239, 5%Pu240) PuO_2

The burnup process is simulated using the GETERA program in this work. This program is intended for the fast and thermal neutron-physical computation of nuclear reactor cells and polycells in spherical, cylindrical, and planar geometries. Utilizing the nuclear data library BNAB-93, the first collision probability approach is used to calculate the neutron-physical characteristics of the reactor lattice [11]. Nuclear data for 135 nuclides in 299 energy categories are available in its library [12]. The program demonstrated an excellent capacity to compute the neutronic characteristics of VVER-type reactors [13].

The burnup process is observed in one cell model considering the central hole of the fuel pellet, and the gas gap between the fuel and cladding. The cell which consists of a fuel rod and coolant is divided into five zones (see Figure 2). Steps for one through calculation are taken at the first five-day-long step which is followed by 38 fifty-day-long steps. Reloads are calculated by considering Kinf (Burnup) as a linear function of time. While drawing graphs of the changes in isotopes concentrations actual values are divided by their maximum values.

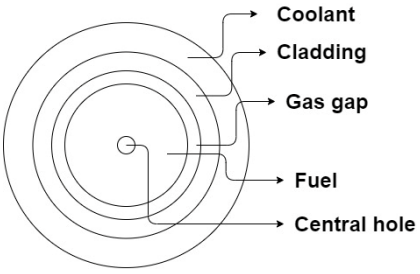

Fig. 2. Unit cell model.

4 Results and discussions

Results of calculations of burnup depths and times are shown in Table 3, for two, three, and four reloads respectively.

Table 3. Dependences of burnup depth and time on reload.

	Two reloads			Tree reloads			Four reloads		
Variants	t, days	Δt, days	Burnup, MWd/kgHM	t, days	Δt, days	Burnup, MWd/kgHM	t, days	Δt, days	Burnup, MWd/kgHM
v1	1384	692	48.12	1555	518	54.12	1659	415	57.73
v10	1043	522	35.94	1172	391	40.43	1250	313	43.12
v12	659	330	22.63	740	247	25.46	789	197	27.15
v13	882	441	30.47	991	330	34.28	1057	264	36.57
v14	1277	639	44.08	1435	478	49.59	1530	383	52.91

4.1 Infinite multiplication factor

The infinite multiplication factor (Kinf) versus burnup on all four conditions is illustrated in Figure 3. From Figure 3 and Table 3 it is vivid that in the case of MOX fuel two interesting features are observed: the first one is maximum Kinf is lower than pure uranium dioxide case, because of the highly effective resonance absorption cross-section of plutonium fertile isotopes. Secondly, the decrease in the Kinf through burnup goes slowly compared to the UO_2 case. This advantage allows for the deployment of less burnable poison and elongates campaign time which increases power plant capacity.

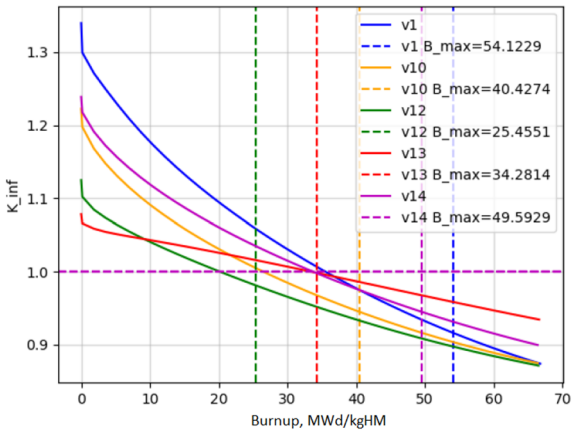

Fig. 3. Dependence of Kinf on the burnup for different variants.

4.2 The behaviors of isotopes in the fuel

From Table 3 and the figures, it is observed that burn-up in plutonium mixture with depleted uranium is smaller for the same "enrichment" of fissile isotopes, because of the high absorption properties of plutonium fertile isotopes. This type of MOX fuel is of practical importance though. Here results with weapons-grade uranium with 95% ^{239}Pu concentration are fairly practicable with about 35-40 MW days/kg burnup. The maximum achieved burnup with 5% weapons-grade plutonium is 49 MW days/kgHM, but this concentration of ^{239}Pu has a small reactivity range up to its β_{eff}. 8 % reactor-grade plutonium with depleted uranium achieved 34 MW days/kgHM burn up, which is about the real achieved burnup in PWRs.

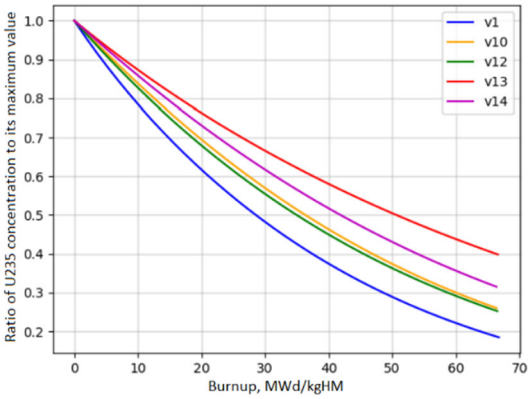

Fig. 4. The behavior of ^{235}U.

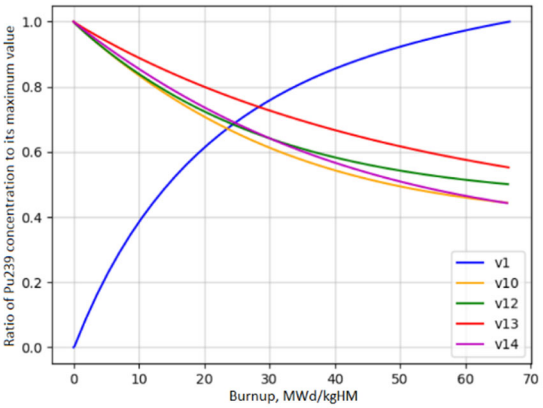

Fig. 5. The behavior of ^{239}Pu.

In the $(U+Pu)O_2$ case ^{239}Pu reduces from its maximum because initially it is more than its asymptotic value and undergoes fission with a greater rate than its buildup from ^{238}U, hence concentration decreases. Except for the case of v13, which has the greatest concentration of ^{240}Pu, in all the cases concentration of ^{240}Pu increases since its initial concentrations are lower than the asymptotic values. Similarly, the same pattern is observed for ^{241}Pu, it can only come to the scene through buildup. Any rapid supercritical excursion would have a shorter timeframe because MOX's neutron production time is likewise shorter than UO_2's. For ^{239}Pu as opposed to ^{235}U, the neutrons in the fission spectrum are more energetic. On the other hand, the moderator and fuel Doppler temperature coefficients of reactivity for MOX cores tend to be more negative than for UO_2 cores due to the significant epithermal absorption resonances in the plutonium isotopes.

The yield of ^{135}Xe from the fission of plutonium and uranium is about equivalent. The extra reactivity required to start up at peak xenon circumstances and the propensity for spatial flux oscillations induced by xenon oscillations are lower in a MOX than a UO_2 core due to the larger thermal absorption cross-section of the plutonium isotopes.

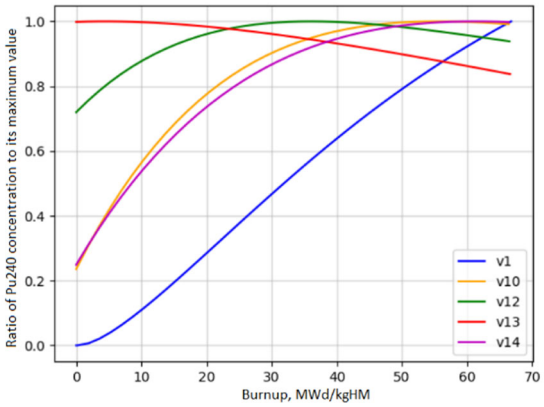

Fig. 6. The behavior of ^{240}Pu.

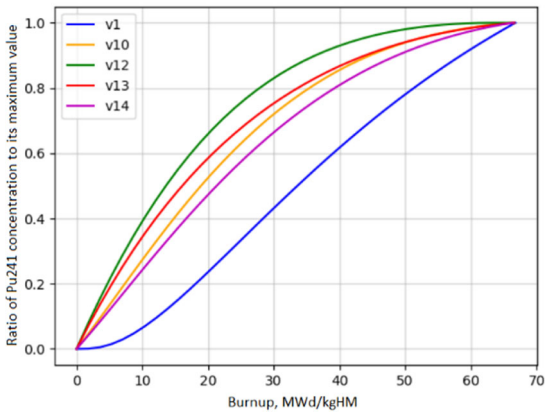

Fig. 7. The behavior of 241Pu.

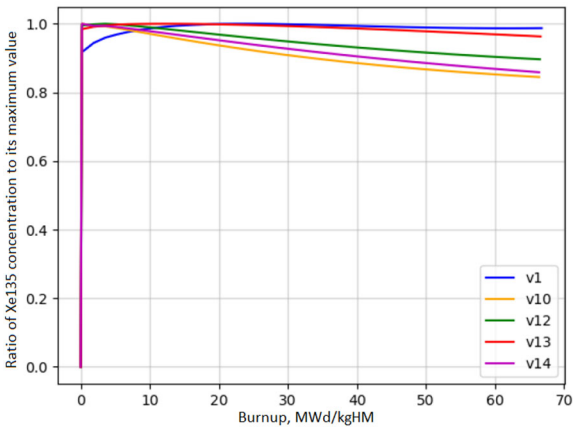

Fig. 8. The behavior of ^{135}Xe.

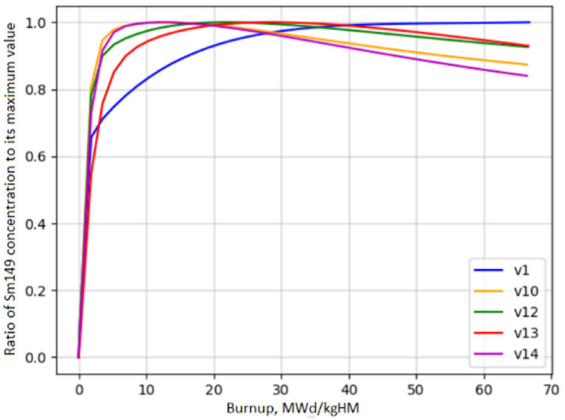

Fig. 9. The behavior of 149Sm.

5 Conclusions

From all the results taken and discussions, it can be concluded that plutonium refueling for PWRs like VVER-1200 has already been achieved by its limited stage but there is still room to develop. Although having complex and sharp behavior plutonium has some characteristics like a higher fuel temperature coefficient than uranium which allows it to be controlled. From the results, it is seen that to achieve desired multiplication factor, less proportion of weapon-grade plutonium is necessary than reactor-grade plutonium. With the limited natural uranium resources future of the nuclear industry is most certainly related to plutonium mixture fuel. Deploying fast and thermal reactors with a known proportion it is possible to achieve a closed fuel cycle.

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