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Investigation on the effect of ^{238}U replacement with ^{232}Th in small modular reactor (SMR) fuel matrix

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ABSTRACT

Effect of ^{238}U replacement with ^{232}Th in small modular reactor fuel matrix was studied. Four different ^{235}U enrichment levels (10, 13.8, 16.5 and 19.8 wt%) were used in a pairwise manner for UO_2 and (ThO_2 + ^{235}U) fuels. The calculation was performed using Monte Carlo N-particle code integrated with CINDER90 for burn-up calculations in a homogeneous fuel assembly. The results show that enrichment level < 17 wt% for thorium fuel produced virtually no plutonium isotopes but became visible only at 19.8 wt% enrichment. The number of neutrons produced per fission (ν) for ThO_2 + ^{235}U was less than that of UO_2 because its averaged contribution from ^{235}U and ^{233}U was smaller compared to the similar contribution from ^{239}Pu, ^{241}Pu and ^{235}U. Large amount of ^{239}Pu and actinides were produced from UO_2 fuel due to the impact of ^{238}U. The reactivity of thorium at the beginning of cycle (BOC) was smaller compared to uranium but higher at end of cycle (EOC) resulting to higher excess reactivity in all thorium fuel. Production of little plutonium isotopes by thorium fuel suggests that it would make a good proliferation resistance fuel and could be used in any W-SMR to incinerate stockpiled plutonium.

1. Introduction

Nuclear technology from early 1940s to the Manhattan project (1940–1960) (Lung and Gremm, 1998) has advanced greatly in power generation and production of medical and industrial isotopes. Notwithstanding the successes recorded in the technology, there are still some challenges and issues surrounding nuclear energy: starting from reactor safety, proliferation risk of spent fuel, waste management and radiation hazards in the event of possible accident or terrorist attack compared to coal, wind, solar, hydropower, oil and gas energy sources (Kessides, 2012; Slovic et al., 1991).

Currently, UO_2 is a dominant nuclear fuel (Anantharaman et al., 2008) used both in civilian and naval reactors which produces the required energy and the accompanying wastes whose management has been a challenge to the industry. Although, several technological developments have provided solution to reactor safety issues, waste management of spent fuel and its associated proliferation risk which depend on the type of fuel used remained challenging. These challenges are based on the nature of actinides and non-actinides produced by the fuel (Humphrey and Khandaker, 2018). Most of these issues, especially the proliferation risk and waste management surrounding uranium-based fuel are attributed largely to the production of plutonium isotopes by its precursor ^{238}U and its subsequent decay products during and after reactor operation. Under irradiation, ^{235}U undergoes fission by thermal neutron absorption while ^{238}U undergoes nuclear transmutation by neutron capture as shown in Eq. (1) to produce fissile ^{239}Pu. Only a negligible fraction of ^{238}U undergoes fission by fast neutron absorption. Subsequently, ^{239}Pu in about 65% of the time fissions by thermal neutron absorption and in 35% of the time produces ^{240}Pu by radiative capture.

$$^{238}\mathrm{U\ (fertile)} \xrightarrow[\substack{\sigma_\gamma=2.86b \\ I_{resonance}=277b}]{(n,\gamma)} {}^{239}\mathrm{U} \xrightarrow[T_{1/2}=23.47\,\mathrm{min}]{\beta^-} {}^{239}\mathrm{N\ p} \xrightarrow[T_{1/2}=2.356d]{\beta^-} \begin{matrix} ^{239}\mathrm{Pu\,(fissile)} \\ \sigma_f = 750b \\ \sigma_\gamma = 27b \end{matrix} \quad (1)$$

Similarly, ^{232}Th undergoes nuclear transmutation by thermal neutron capture and subsequent beta minus decay to produce fissile ^{233}U as

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