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Reducing the plutonium stockpile around the world using a new design of VVER-1200 assembly

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ABSTRACT

The broad goal of this work is to use the accumulated plutonium around the world in peaceful uses of energy production rather than for military purposes. This work investigates the feasibility of burning the Pu vector that is extracted from the spent fuel of light water reactor or from the nuclear warheads stockpile. MCNPX code version 2.7 has been used to design two assembly models, conventional assembly and Blanket-seed (BS) assembly. The conventional assembly is fueled with UO_2 while the BS assembly is fueled with ThO_2 in the blanket region and Pu vector either in the form of reactor grade plutonium (rgPu) or weapon grade plutonium (wgPu) in the seed region. Using of Th-232 as a fertile material in the blanket region prevents from more Pu breeding and enables a longer fuel burnup rate. Five different fuel models are studied to investigate the optimum concentration of Pu vector that is used in the seed region. MCNPX code is used to simulate the neutronic characteristics of the presented fuels. The multiplication factor K_{eff} values of the suggested fuel in the BS assembly have been analyzed and compared with that obtained in the conventional assembly. Some parameters related to safety operation such as moderator temperature coefficient (MTC) and effective delayed neutron fraction (β_{eff}) have been calculated. The Pu vector concentrations have been investigated with burnup to distinguish the effectively of the suggested models to burn how much of the used Pu in the seed region. Using of Th-232 as a fertile material in the blanket region enhance the ability of BS assembly to bred more fissile material (U-233). Therefore, the suggested fuel assemblies achieve a higher conversion ratio (CR). The radioactivity of the actinides and non-actinides elements has been investigated with burnup. Due to the poising effect of fission products on the reactivity of the reaction, it is important to investigate the concentrations of the most important fission product at the presented fuel.

1. Introduction

The accumulation of the nuclear wastes from the commercial reactor is one of the significant obstacles that face the nuclear industry. This work aims to burn the rgPu) and wgPu during the operation of VVER-1200 using BS assembly. The BS assembly is considered the most promising assembly as it has the ability to consume a large amount of nuclear waste. The nuclear waste materials are classified as fission products, structural materials and actinides defined as hazardous radioactive waste because of their high-level radiotoxicity (Costa and Pereira, 2003).

The continuous production of radioactive nuclides is considered the main problems that face the LWR operator. This material has to be contained safely during reactor operation. After spent fuel discharging, it must be disposed of in a safe and economic way. The production of these nuclides cannot be avoided in conventional LWR that is fueled with UO_2 fuel as this fuel is low enriched uranium (i.e. containing more than 90% of U-238) (Mittag and Kliem, 2011). The current practice of Pu recycling in existing LWRs in the form of U-Pu mixed oxide fuel (MOX) is not efficient due to continuous Pu production from U-238. Using of Pu as a MOX fuel in PWR permits The use of Th-Pu mixed oxide fuel will considerably improve Pu consumption rates because virtually no new Pu is generated from thorium (Fridman and Kliem, 2011).

Fertile U-238 is the main source for the high quantities of long-lived radioactive actinides. The replacement of U-238 with Th-232 will not only yield greater quantities of new fissile material but also produce lower waste inventories and radio-toxicities. A further advantage is that unlike 233U, plutonium produced from standard UO_2 fuels is a wasting asset due to the short half-life of the fissile Pu-241 which decays to non-fissile Am-241 (Rose et al., 2011).

Bjork (2013) develops a fuel assembly design for thorium-plutonium fuel. The developed assembly aimed to maximize the

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amount of energy that can be extracted from a certain amount of plutonium while maintaining acceptable values of the neutronic safety parameters such as reactivity coefficients, shutdown margins and power distribution.

Using of plutonium extracted from the spent fuel of LWRs in the seed region is necessary for converting Th to U-233. High conversion can be achieved using a heterogeneous BS assembly design. Increasing the CR in existing PWRs can potentially improve the utilization of natural resources, through the exploitation of vast thorium reserves and reduction in natural uranium demand. The seed rods work as a neutron supplier, while the blanket rods act as a U-233 breeder (Baldova, et al. 2014).

The Pu generated during the burnup of a standard LWR fuel is considered the main source of proliferation potential and radiotoxicity. A significant reduction in quantity of Pu may be achieved by replacing the U-238 by Th-232. Two different designs were considered: homogeneous and heterogeneous. The homogeneous design uses a mixture of ThO_2 and UO_2, with a uranium volume fraction and enrichment sufficient to obtain the required burnup and cycle length. The heterogeneous design concept considered in this paper, known as Radkowsky Thorium Fuel (RTF), The fuel-to-moderator ratios in the seed and blanket regions are different, and optimized to reduce Pu production in the seed, and enhance U-233 production and burning in the blanket (Radkowsky and Galperin, 1998).

Due to the serious public and political concern in the world about misuse of the plutonium and about accidental release of highly radiotoxic material into the environment, it therefore becomes necessary to keep the plutonium under strong security. One alternative for the management of plutonium is to incinerate it in reactors. But if the plutonium is fueled in reactors in the form of uranium/plutonium mixed oxide (MOX), second-generation plutonium is produced. A possible solution to this problem is to incinerate plutonium in combination with thorium. This document aims to minimize the plutonium production and maximizing the plutonium incineration. A heterogeneous, BS fuel assembly design was adopted. The main design approach is to use plutonium as a seed fuel providing neutrons to a subcritical blanket loaded mainly with thorium (IAEA-TECDOC-1349).

Raitses et al. (2012) utilize the seed-blanket fuel assembly instead of conventional assembly in either a Russian pressurized water reactor (VVER-1000) or a Western pressurized water reactor (PWR). The separation of fissile and fertile allows separate fuel management schemes for the thorium part of the fuel (blanket) and the driving part of the core seed. Thorium based spent fuel also contains fewer higher actinides, hence reducing the long-term radioactivity of the spent fuel.

Nuclear experts in many countries are interested in the thorium-fuel cycle because thorium has a more abundant resource than uranium and it can be used to destroy a significant amount of the accumulated Pu around the world (Trellue et al., 2011).

Puill and Bergeron (1997) presents an advanced Plutonium Fuel Assembly concept, based on a uranium-free plutonium fuel. This design achieved high burnups and an increased moderation ratio, enables 60% of the second-generation plutonium to be consumed, while the minor actinides produced only represent 8% of this figure. This assembly is made of 36 thick annular rods and of 120 standard UO2 rods with low enriched uranium and Zircaloy-4 clads. The heterogeneous design of the fuel assembly which includes natural uranium or low-enriched uranium fuel rods guarantees values that suit the physical parameters of the core.

The Pu consumption rate may be further enhanced by putting the Pu on an inert matrix (TRU-40Zr). However, the absence of the 238U in the inert material affects negatively neutronic safety parameters (Youinou et al., 1999).

The fuel discharged from the LWRs may be used after undergoing only limited processing that will remove its cladding, remove the gaseous and volatile fission. Pu recovered from the LWRs is fed to the seed of the (blanket and seed) core as a U-Pu-Zr ternary metallic fuel while the blanket rods are fueled with thorium. Instead of running the thorium blanket of the S&B reactor in a once-through mode and accumulating a large inventory of Trans-Th elements, Greenspan (2015) assesses the feasibility of using the discharged Trans-Th to feed PWRs that operate on a closed fuel cycle that their fuel is recycled. This fuel cycle option provides a possible solution to the large amount of 233U bred in the S&B core whose decay daughters are the major contributors to the radioactivity and radiotoxicity in the long-term. The broad goal of this work is to develop a safe and reliable VVER-1200 fuel which effectively consumes the accumulated Pu around the world.

2. Dimensions of the suggested assembly

VVER-1200 is used as a reference in the suggested design in this paper. VVER-1200 is considered the most promising reactor due to their high safety precaution. The VVER-1200 core consists of 163 assemblies. All of these assemblies have the same dimensions and the same number of fuel rods. The fuel rod diameter is homogeneous through the whole assembly as illustrated in Fig. 1 (Galahom, 2017). The dimension of suggested assembly is the same of the original assembly except that the fuel rod in the assembly is divided into two spatial regions; an external region (blanket) and internal region (seed). The blanket rods are fueled with a fertile material while the seed rods are fueled with a fissile material. The surface of seed fuel is adequate to sustain required temperature and heat flux values. The blanket region contains 204 fuel rods while the number of the seed rod is 108. Table 1 illustrates the dimensions of the suggested assembly. In this study, the neutronic characteristics of the three dimension VVER-1200 fuel assembly were performed using neutron transport code MCNPX version 2.7 with ENDF/B-VII.0 cross-section library. In the MCNPX code, number of source histories per cycle is 70,000, and number of cycle to be skipped is 30 and total number of cycle is given as 120. The standard deviation k-eff is about 0.0017. Fig. 2 illustrates the horizontal cross cross-section of VVER-1200 BS assembly.

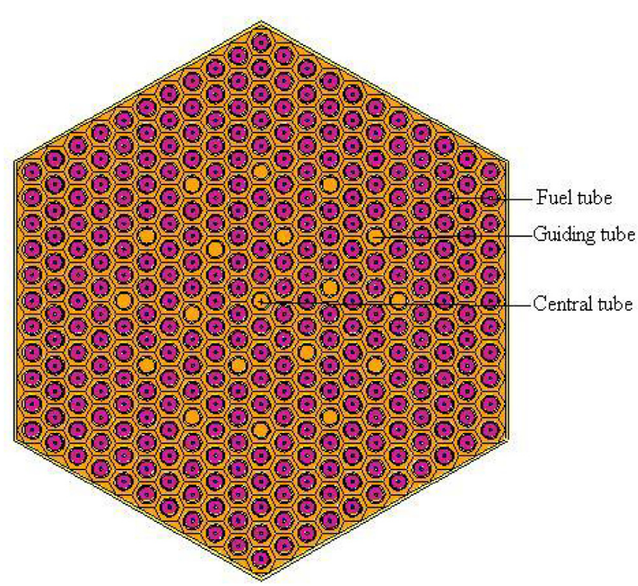

Fig. 1. A layout of a horizontal cross-section of conventional VVER-1200 assembly.