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Neutronic analysis of denaturing plutonium in a thorium fusion breeder and power flattening

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Abstract

The purpose of this study is to denature nuclear weapon grade quality plutonium in a thorium fusion breeder. Ten fuel rods containing the mixture of ThO_2 and PuO_2 are placed in a radial direction in the fissile zone where ThO_2 is mixed with variable amounts of PuO_2 to obtain a quasi-constant nuclear heat production density. The plutonium composition volume fractions in the fuel rods are gradually increased from 0.1% to 1% by 0.1% increments. The fissile fuel zone is cooled with four various coolants with a volume fraction ratio of 1 ($V_{coolant}/V_{fuel} = 1$). These coolants are helium gas, flibe "Li_2BeF_4", natural lithium and eutectic lithium "$Li_{17}Pb_{83}$". Nuclear weapon grade quality ^{239}Pu in the fuel composition is denatured due to the accumulation of the ^{240}Pu isotope in the fissile zone after 18 months of plant operations. Under a first wall fusion neutron current load of 2.222×10^{14} (14.1 MeV n/cm^{2}s), which corresponds to 5 MW/m^2, by a plant factor of 100%, at the end of the plant operation, the fissile fuel enrichment quality between 6.0% and 10% is obtained depending on the coolant types. During the plant operation, the tritium breeding ratio (TBR) should be at least 1.05. In the selected blanket, only the flibe coolant is already self sustaining at start up. The TBR increases steadily due to the higher neutron multiplication rate during the plant operation period. The highest TBR is obtained for the eutectic lithium coolant 1.4035, followed by the flibe coolant 1.3095, helium gas coolant 1.2172 and natural lithium coolant 1.0553 at the end of the operation period of 48 months. The energy multiplication factor M changed between 2.1731 and 6.6241 depending on coolant type during the operation period. The peak to average fission power density ratio Γ in the blanket decreases

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by ∼15%, which allows a more uniform power generation in the fissile zone. The isotopic percentage of ^{240}Pu reaches higher than 5% in all coolant types. This is very important for international safety.

Keywords: Hybrid reactor; Power flattening; Denaturation; Plutonium; Thorium

1. Introduction

In recent years, there is a great interest for new energy sources due to an increase in energy demand. Nuclear energy is one of the important potential candidates for new energy sources. Today, most of the nuclear electricity is produced by light water reactors (LWRs) using low enriched fissile fuel (∼3.5% enrichment), followed by the Canada deuterium uranium (CANDU) reactors using natural uranium (∼0.71% enrichment). Existing nuclear power plants can utilize only a small fraction of natural uranium, and the remainder can not be used for energy production.

A hybrid reactor can operate commercially with a very modest fusion driver of low energy gain ratio due to the extensive energy multiplication of the overall system, i.e., the blanket and the client fission reactor [1]. Studies show that it can produce up to 30 times more fissile fuel than that of a fast breeder reactor (FBR) per unit of energy. Typically, for a hybrid reactor (HR) with suppressed fission, the breeding ratio (BR) per respective nuclear reaction energy (E)

$$\frac{\left(\frac{\mathrm{BR}-1}{E}\right)_{\mathrm{HR}}}{\left(\frac{\mathrm{BR}-1}{E}\right)_{\mathrm{FBR}}} = \frac{\left(\frac{1.8-1}{27}\right)}{\left(\frac{1.2-1}{200}\right)} = 30 \tag{1}$$

can be obtained [2].

Early commercialization of the hybrid reactor will accelerate the development of pure fission power plants, and it would also accelerate the deployment of the FBRs with the extensive supply of start up inventory. A FBR needs precious plutonium material for start up, whereas the hybrid reactor starts out using natural or depleted uranium or thorium. In the past, various studies have been conducted on fusion breeders [2–7].

At present, thorium is very attractive as a nuclear reactor fuel since world thorium reserves are estimated to be about three times more abundant than natural uranium reserves. Many researchers have investigated the neutronic performance parameters of the hybrid reactor fuelled with thorium [8–17]. Existing nuclear power plants fuelled with uranium are producing nuclear weapon grade quality ^{239}Pu > 95% in the fissile components. This fissile component accumulating in critical reactors is a valuable nuclear fuel. In this study, the denaturizing of nuclear weapon grade quality ^{239}Pu is investigated in a hybrid reactor fuelled with thorium.

The fissile zone of a hybrid reactor is a fusion neutron source driven medium. Hence, the neutron fluxes, which are proportional to the nuclear heat production, tend to have an exponentially decreasing character in the fusion neutron source driven medium. A non-uniform fission power density is the major source for the temperature and radiation gradients, which complicate fuel shuffling scenarios. On the other hand, a quasi-constant fission power generation has several advantages, such as reduced material stresses, uniform exploitation of the fissile zone, higher fuel burn up grades etc. [18]. An elegant and easy way of fission power flattening is possible by increasing the macroscopic fission cross section (Σ_f) in the radial direction in order to compensate for the